6-2005

A Framework for Routing and Topological Decision-Making within a Transformational Communications Architecture

Alexander I. Smith

A FRAMEWORK FOR ROUTING AND TOPOLOGICAL DECISION-MAKING WITHIN A TRANSFORMATIONAL COMMUNICATIONS ARCHITECTURE

THESIS

Alexander I. Smith, Major, USAF

AFIT/GCS/ENG/05-21

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GCS/ENG/05-21

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THESIS

Presented to the Faculty

Department of Electrical and Computer Engineering

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science

Alexander I. Smith, BA

Major, USAF

June 2005

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Alexander I. Smith, BA

Major, USAF

Approved:

/signed/	10 Jun 05
Scott R. Graham, Maj, USAF (Chairman)	Date
/signed/	10 Jun 05
Rusty O. Baldwin, PhD (Member)	Date
/signed/	10 Jun 05
Robert F. Mills, PhD (Member)	Date

AFIT/GCS/ENG/05-21

Abstract

A Transformational Communications Architecture (TCA) has been proposed by the US government with the goal of creating "an Internet in the sky." This thesis presents a framework which places user requirements at the heart of routing and topological decision-making within the TCA. It provides new terminology to describe data transmissions and link characteristics and an approach to formulating cost functions to better meet user needs. The framework is intended to stimulate interest and focus efforts on how to meet military specific requirements by taking advantage of the TCA's diverse capabilities and topology. Cost functions using newly-defined parameters are simulated and shown to improve relevant performance over a traditional routing approach.

Acknowledgments

I thank God, my family, and the USAF for giving me the strength, resources, and opportunity required to complete this effort. I thank my advisor, Major Scott R. Graham, PhD and Dr. Kenneth Hopkinson, for their guidance, patience, and assistance during this challenging and exciting time. I also thank Dr. Rusty O. Baldwin and Dr. Robert F. Mills for their classroom instruction, philosophical insight, and willingness to serve on my thesis committee.

Alexander I. Smith

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A FRAMEWORK FOR ROUTING AND TOPOLOGICAL DECISION-MAKING WITHIN A TRANSFORMATIONAL COMMUNICATIONS ARCHITECTURE

I. Introduction

Background

The U.S. military has always needed to share information. That need has not diminished with advances in technology. Data links such as Link-16 met some of the information sharing requirements, while other new systems were developed to meet mission specific needs. The differences between many systems resulted in incompatible data formats which required translation in order to share data.

The development of the Internet changed expectations of how rapidly information can be accessed. These expectations were amplified as capabilities for transmitting and receiving data vastly improved. Fiber-optics brought high-speed backbone connections which are faster than those that are copper-based. Standards such as the American National Standard Institute's Fiber Distributed Data Interface (FDDI) help ensure compatibility between products from different vendors. Speed improvements based on fiber-optic technology did not transfer into airborne systems which used air, not copper wires, as their medium for passing data.

The U.S. military have fought in several conflicts where the ability to rapidly access and pass information was critical for success. Without the proper infrastructure the connectivity to pass information could not be achieved. The vision of connecting all warfighters grew into a concept that called for the integration of communications systems, computers, and information management resources into a global information grid. However, a radical transformation of military communications capabilities and infrastructure is required to interconnect U.S. military forces in the air, on land, or at sea, throughout the world

The Department of Defense conducted a Transformational Communications Study which concluded that the U.S. communications architecture needs to be transformed in order to meet future requirements (GlobalSecurity.org, 2003). The next-generation of communications capabilities, the Transformational Communications Architecture, will be an “Internet in the sky” providing end-to-end connectivity necessary to extend access to the global information grid to warfighters everywhere. This new architecture includes diverse technologies which require new approaches to routing information.

Problem Statement

Routing algorithms have used various metrics for determining routes. Path length, reliability, delay, bandwidth, load, and communication cost have all been used as routing metrics, with path length being the most common (Cisco Systems Inc., 2002). In a military environment, the requirements of the warfighter must be considered to improve the probability of mission success. The metrics stated above do not consider the diverse transmission technologies found within the Transformational Communication Architecture, and are inadequate for addressing some important military-specific requirements such as the need to avoid detection.

Research Objectives

The goal of this research is to create terminology and metrics specific to warfighters' requirements as part of a framework for routing and topological decision-making within a Transformational Communications Architecture. There are two objectives. The first objective is to create terminology adequate for capturing the communications requirements of military users. The second objective is to create a cost function which considers the topology of the Transformational Communications Architecture and elicits a network routing behavior consistent with identified user requirements.

Methodology

This research identifies terminology required to adequately describe communications requirements and incorporates that terminology into a cost function to be used in packet routing. A network simulation is performed using routing paths consistent with the new cost function, and an analysis comparing the new routing method to a standard method shows the feasibility of this approach.

Scope

The NS2 discrete event network simulator is used to route traffic originating and terminating at a set of pre-determined nodes. Two cost function parameters are varied to create four scenarios to represent four classes of traffic which are routed based on their cost function values. The same set of source and destination nodes is used in each of the scenarios. The costs for each class of traffic are calculated manually and the NS2 routing table is modified by changing simulation software code for each of the scenarios. Results from each of the scenarios are compared to results obtained from routing based on Dijkstra's All-Pairs algorithm.

Summary

The primary focus of this research is to identify new terminology as parameters to capture communications requirements of military users and to use that terminology to effectively route information using the Transformational Communications Architecture.

II. Literature Review

The Need to Share Information

The need to share information has consistently been addressed in the post-action analysis of every major conflict in recent history. The sharing of a single secure satellite communications channel by everyone ranging from commanders to tactical users during the invasion of Grenada is one example of how limited resources forced information to be shared (Anno and Einspahr, 1988:41). Following Operation Allied Force in Kosovo, Gen John P. Jumper stated “In another shortfall, our secure communications capabilities were insufficient and many of our transmissions were made ‘in the clear.’ As a result, sensitive information sometimes fell into enemy hands.” (Jumper, Testimony to Congress: 1999) Calls for systems which share information more effectively, as well as organizations willing to share information, have been repeatedly identified in post-war “lessons learned.” But before agreement can be reached on what is lacking, a common language with specific terminology must be agreed upon to describe the problems and formulate solutions.

As the demand for rapid access to current information grows, new methods to enable information sharing must accommodate the demand. Some of these methods include improved physical infrastructures; others include new ways of thinking about how to get the right information to the right place at the right time. All methods will need to have a common framework to enable meaningful discussion and comparison.

To better understand where military information sharing is going, it helps to understand where it’s been and where it is currently. Conflict and the threat of conflict has always been a driving force behind military developments. As the saying goes, "Necessity is the mother of invention." The nation's need for security drives improvements in defense, including more effective command and control and better access to information.

Development of Tactical Data Sharing

Tactical data sharing is an integral part of defending the nation's airspace. The air defense mission requires timely information with rapid updates to maintain an accurate estimate of the current air battle. This "air picture" must have the fidelity to track adversaries, and effectively target them. The volume of data required to accomplish the air defense mission exceeds human capacity to express with simple voice systems, so data must be shared using data links which enable machine-to-machine connectivity, with human intervention being the exception. In addition to enabling the air picture, command and control (C^2) systems must provide timely information, enabling users to positively affect the situation (Golliday, 1985:779).

The Tactical Digital Information Link (TADIL), a data link designed by the U.S. military, creates a tactical network capable of disseminating information during conflict. The requirements for data links were designed with military conflict in mind.

> The data link is the electronic equipment, including protocols and messages, that permits transmission of information in digital form. As a basic requirement, data links must securely support the maintenance of a high-density rapidly changing air picture in real time in a hostile environment. Specifically, data links must have sufficient timeliness, capacity, security, and survivability among other requirements. Furthermore, data links must have sufficient flexibility for interconnection to support interoperability among the units in a tactical data system. (Golliday, 1985:779)

Data links share information via point-to-point connections between two users or netted connections between many users. This can raise the level of awareness at specific locations or throughout an entire region. Historically, military data links were designed to work with specific systems and do not interoperate. Figure 1 shows a data link network with airborne elements as well as ground units.

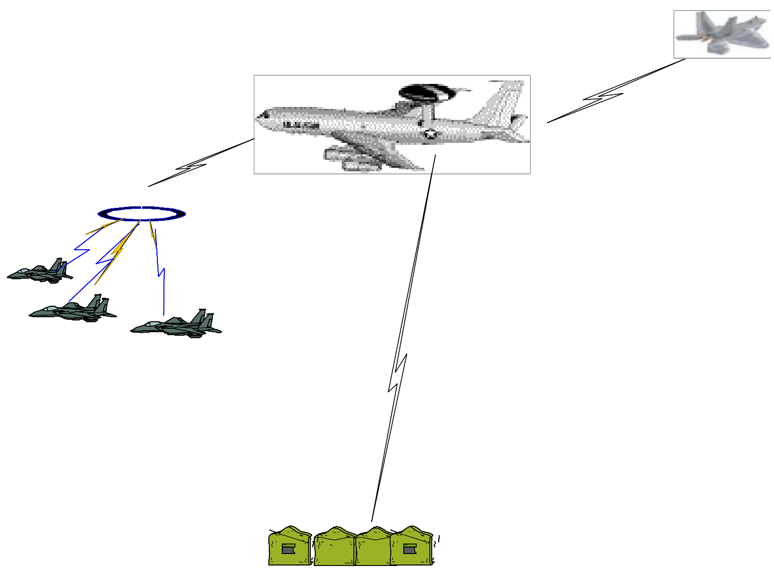

Figure 1. A Data Link Network

Stovepipe Systems

Data links were developed for specific requirements, with each data link being characterized as either tactical, intelligence surveillance reconnaissance (ISR), or command and control (C^2). The similarity between links within a given functional area is generally greater than that between links from different functional areas. In short, the systems were designed to work together within their own functional areas, but can't directly pass data to other functional areas.

For data to be shared with all interested parties, there must be at least one system capable of taking data from one type of data link and translating it into formats usable by other data links. A common data link capable of translating various data formats could have a hub in a hub-spoke topology, with translating capability similar to a computer network bridge, broadcasting data from one networked node to all of the other networked nodes. By placing the critical node at the hub, the ability to communicate with non-homogenous nodes provides a robust ability to access information through an assortment different links. The Airborne Warning and Control System (AWACS) radar plane in is an example of a hub which is linked to other aircraft and ground units using different data formats.

Dissimilarities between the data format in each system requires translation, introducing delays. In addition, maintaining data interoperability is complicated by the need to synchronize changes to the data format in any one system with any other systems with which it communicates. In the case of hubs, the ability to translate data may be temporarily lost.

As an example, during the 1990's, an Air Weapons Controller working at an Air Defense Sector in the U.S. provided the physical hub. One night a drug smuggler attempted to fly his airplane into Canada. The Royal Canadian Mounted Police (RCMP) had an aircraft following the criminal, but due to the radio range limitations couldn't communicate with it. They could, however, communicate with the Air Weapons

Controller, almost a thousand miles away, over a phone line; and he had the capability to connect their phone call through radios in the vicinity of the pursuit. The RCMP aircraft followed the smuggler to his landing strip in Canada, and following a brief escape attempt, captured him on the ground. In his role at the network hub, the Air Weapons Controller was able to provide an interface between two incompatible systems (telephone and radio) and make a connection between two end nodes which needed to share information. Such human intervention isn't always feasible.

Advances in Technology

Major changes in the world often follow scientific breakthroughs or advances in technology. Information technology has experienced rapid changes over the past few years.

Internet.

The Internet changed the world, not only by changing what information can be accessed, but by changing expectations of what information can be accessed, and how quickly. Military users also have a greater demand for immediate access to information. The U.S. Army's communications requirement was up to 10 times larger than the available supply. Shortfalls in supply are projected to persist beyond the year 2010. Since costly planned growth cannot keep up with the demand, better bandwidth management, replacement of bandwidth-intensive video teleconferencing applications with simple teleconferencing plus whiteboard applications, and elimination of excessive video downlinks from unmanned aerial vehicles (UAV) will help eliminate lower-priority traffic (Congressional Budget Office, 2003:xii-xiii).

The so called "World Wide Web" of information has become synonymous with ease-of-use partly because the protocols and interfaces make interoperability a reality. The Internet's complexity has been abstracted into simple "point-and-click" action that is easily learned and understood. The Internet Protocol (IP) is widely accepted and is now used throughout the world as the primary carrier of data information. This acceptance has enabled a growth in interoperability and the interconnection of systems on a grand scale (Bergzén, 2000:29).

Fiber-optics.

Advances in laser technology have greatly increased the amount of data one fiber optic link can carry. Fibers have lower noise, hence can achieve a higher data rate. Lasers are immune to the electromagnetic interference wires are susceptible to. The result is fewer retransmissions due to errors.

Most importantly, the theoretical limit for the information carrying capacity of lasers is phenomenal:

> For the future, the ultimate potential of a single mode fiber has been estimated. It is about 25,000 Gbs (25,000,000,000,000 bits per second). At that rate you could transmit all the knowledge recorded since the beginning of time in 20 seconds. (Newton, 2001:395)

Wireless.

The Air Force vision of future wireless communications networks includes both free-space optics (laser) and radio frequency communications capabilities (Teets, 2002). The vision increases communications capabilities within the Department of Defense and intelligence community by a factor of 10 through the inclusion of laser communications in the communications architecture.

Even so, laser links have problems as well. For example, laser links through free-space pose a challenge to link maintenance due to weather conditions and pollution.

New techniques which show promise in overcoming problems associated with penetrating clouds and other adverse weather conditions are currently in development. Researchers have attained average bit rates higher than conventional optical wireless links operating at 2.5 Gbps. (*The Next Wave*:2004)

Radios.

Current tactical radios were developed to meet the mission-specific requirements of their respective services. Specialized requirements led to incompatibility between radios. The Joint Tactical Radio System (JTRS) program is addressing many of the interoperability issues by clustering radios into groups based on similar characteristics. Each cluster builds upon a common hardware baseline which is modular, scaleable, and backwards-compatible enabling growth of capabilities, bandwidth, and the addition of network routing capability. JTRS radios will eventually serve as routers on tactical radio networks, possibly replacing the dedicated data links currently in use. Figure 2 shows the JTRS components and their relationship. (JTRS Joint Program Office, 2004)

The waveforms within the JTRS are software versions of radio waveforms used by legacy systems. These waveforms provide backwards-compatibility. The wideband networking waveform is a new waveform designed to meet emerging communication requirements such as networking, secure communication, and higher capacity. Minimal network services provide the means for digital information exchanges. Together, these three components form the core framework of a JTRS radio set. The programmable radio hardware utilizes the core framework to provide the capability to communicate—transmit, receive, bridge, and gateway—using different waveforms and protocols.

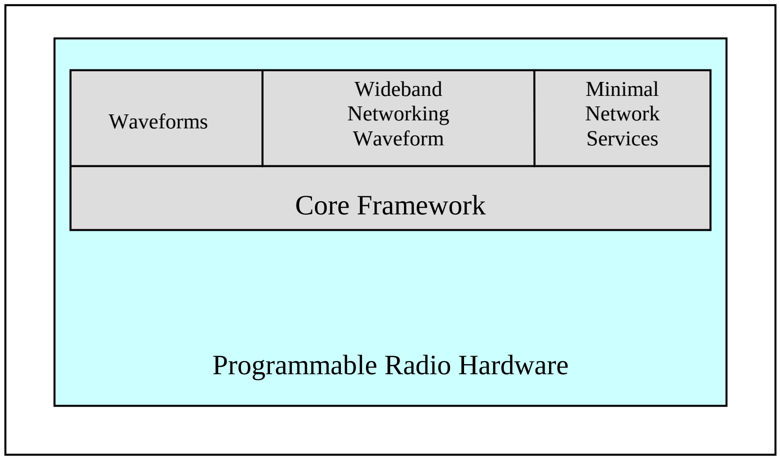

Figure 2. Components of the Joint Tactical Radio Set (JTRS JPO, 2004)

Routing

Once a node has multiple links, it must have a way to determine what information should go to which link. Putting routers into tactical radios to create networks can be complex and requires a basic understanding of the differences between the different types of networks being considered. Regardless of the medium used to transfer information from a source node to a destination node, at some point a decision must be made about how the information must be forwarded. An important routing factor is the topology of the network in question.

Fixed Topology.

In a fixed network links between nodes are static. At times, a route may be unavailable due to link failure, but a given route will always lead to the same destination until the topology is reconfigured. By representing the network as a graph, a hierarchical addressing system may be imposed on the topology, and create a logical representation of the network (Peterson and Davie, 2003:271-299).

With hierarchical addressing, very large networks may be supported because network routers only need detailed information about destinations in their immediate vicinity. However, it is difficult to change a hierarchical addressing scheme once it has been established. Consequently, a hierarchical addressing scheme may not be the best choice when the network topology changes frequently (Comer, 2000:154). Furthermore, the military environment requires dynamic topologies.

Dynamic Topology.

All networks have periods when links are unavailable, and traffic must be routed over alternate paths to reach its intended destination. Simply having links go down and come back up creates a dynamic topology. In this context, however, a dynamic topology is one where a link may be removed and a different link may be added. The network graphs before and after the link change are structurally different. The implication is that the topology is changed to achieve better performance, connectivity, or another desired effect.

Another way for a topology to be dynamic is for nodes to join or depart the network. A joining node will create at least one new link which didn't already exist, and a departing node will remove at least one existing link. Keeping track of which nodes have joined, which nodes have departed, and which nodes are linked at a particular point in time can be complicated because new changes are occurring even as the previous changes are being recorded. Wireless networks must deal with the very issues discussed above.

In a network where all nodes are mobile, wireless, and have omnidirectional transceivers, some nodes will be within communication range of each other and some will not. It may be beneficial for nodes within range to maintain a listing of whom they can communicate with, most likely their nearest physical neighbors. As information intended for a downstream node arrives, it must be forwarded to neighbors who will attempt to get the information closer to its intended destination.

If there is no centrally controlled entity which is tracking all nodes, there will be no global knowledge of where all nodes in the network are located at an arbitrary time. Without knowledge of the complete path to a destination, each node will transmit information to its immediate neighbors who will repeat the transmission until the information "ripples" through the network to its intended destination node. Since every node shares the communications medium with its immediate neighbors, each transmission from one node will result in repeated transmissions from each of the surrounding nodes. This will tie up the communications channel for all nodes in the immediate vicinity, even though many of them have already heard and retransmitted the message. As the number of nodes grows, these retransmissions will tie up the communications channel, resulting in a lower throughput for each node. "Some implications may be worth considering by designers. Since the throughput furnished to each user diminishes to zero as the number of users is increased, perhaps networks connecting smaller numbers of users, or featuring connections mostly with nearby neighbors, may be more likely to be (sic) find acceptance." (Gupta and Kumar, 2000:2)

Given these findings, wireless networks where the links are unidirectional should be considered.

Reconfigurable Topology.

A reconfigurable topology is a specific type of dynamic topology where directionality of the links allows the specification of which pairs of nodes are connected. The intent is to deliberately control the topology to cause a desired effect.

Most topologies have one existing link between any two nodes, although it is possible to have multiple links. For example, two nodes may be connected by a wire and also by a laser link. The laser may be the default method of transmission, but the wire link could be used when electromagnetic interference was low and not degrading the transmitted signal noticeably. Both could be used simultaneously to take advantage of all of the available bandwidth. While having more than one link between two nodes is flexible, it can add to the complexity of representation within a routing table.

A reconfigurable topology where nodes join and depart the network poses challenges in keeping track of what paths are available at any given time. One approach is to store the end-to-end path information at each node and then update it when it changed. If the number of nodes in a network is small enough, end-to-end routes could be stored for every node. Each node could communicate with its neighbors to build a connectivity graph for the entire network. As the topology changed, or was altered, the graph would be updated. This approach does not scale. To alleviate some of the scaling problems associated with large networks, a hierarchical topology and the Border Gateway Protocol (BGP) may be employed (Perlman, 2000:434). BGP indicates whether or not a destination is reachable—it does not guarantee an optimal route even if the destination is reachable. The fact that a destination is reachable does not provide a metric which can be used to assign a cost to each every route to a destination. Most other routing protocols assign an integer cost, such as hop count (Perlman, 2000:439).

Well-known approaches to routing in dynamic networks don't attempt to store end-to-end routing information for all destinations at every node. In Dynamic Source Routing (DSR), for example, source nodes maintain a tree reflecting known routes which are discovered using a route request packet and are maintained using packet updates. Each route is deleted after a set expiration time and must be rediscovered. Ad-hoc On-Demand Distance Vector Routing (AODV) uses routing information stored at intermediate nodes. Source nodes still initiate path discovery with a request packet, but intermediate nodes store the required routing information when the destination node responds. Like DSR, routes in AODV may also be maintained using packet updates. Unlike DSR, AODV uses various timers to denote the expiration of forward, reverse, and active paths to the destination node (Pisai, 2001).

Given the dynamic and reconfigurable nature of the network under discussion, a new approach to assigning cost is needed to prioritize the use of the bandwidth available.

Decision Making and Information Representation

The ability to make decisions is tied to the meaning assigned to different outcomes. There are well-documented approaches to decision making when there are uncertain factors affecting the outcome or when there are multiple attributes affected by each action (Winston, 1994:771-778). The operational sciences deal with decision making and optimization problems where weights are assigned to attributes based on their importance and solutions which maximize or minimize some objective function are found.

Cost and Value Functions.

When all attributes affecting a decision are known, it is possible to assign either a cost or a value to each attribute, with a prioritization of each attribute's relative importance. If costs are additive, then the total cost and total value for the decision maker are calculated as:

$$c(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} c_i(x_i) \tag{1}$$

where c_i is the cost associated with each alternative x_i.; and

$$v(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} v_i(x_i) \tag{2}$$

where v_i is the value associated with each alternative x_i (Winston, 1994:774).

Transformation

> Transformation is a process by which the military achieves and maintains advantage through changes in operational concepts, organization, and/or technologies that significantly improve its warfighting capabilities or ability to meet the demands of a changing security environment. (USAF Transformation Flight Plan)

Since 1990, the U.S. military has been transforming from an industrial-age to an information-age force, and from a Cold War to a post-Cold War force. Transformation is ongoing and affects all aspects of the USAF including culture, capabilities, and business processes.

Transformation requires a long-term commitment and the USAF's strategy calls for developing "transformational" capabilities to support the six "Critical Operational Goals of Transformation" that emerged from the 2001 Quadrennial Defense Review (QDR). One of the six goals is discussed below: "Leverage information technology and innovative concepts to develop interoperable Joint C4ISR."

The QDR emphasized end-to-end Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance (C4ISR) capabilities. Future operational effectiveness will be dependent upon the Department of Defense's ability to share information both internally and externally, and is the motivation for building a Transformational Communications Architecture (TCA). The Global Information Grid and how it supports the needs of warfighters is a critical element of the TCA.

Global Information Grid.

> The global information grid (GIG) is an adaptive entity that integrates communications systems, computers and information management resources into an intelligent system-of-systems. Each component of the GIG exchanges information with other components, enabling the entire infrastructure to adapt to user requirements and to stresses imposed on the network. This adaptability also enables the infrastructure to scale as necessary to support force structure(s) of arbitrary size, or to incorporate new processing, network and communications technologies. (GlobalSecurity.org, 2003)

The GIG is a concept, moving towards an operational capability, and its ability to exchange information has the potential to be limited due to connectivity and interoperability shortfalls. The TCA attempts to address these issues and extend GIG access to more warfighters.

Transformational Communications Architecture.

The Transformational Communications Architecture (TCA) is an end-to-end architecture that will enable the GIG and traverses the four segment domains of the DoD-IC-NASA communications infrastructure. The terminal segment is composed of end-users, ground stations, as well as space and airborne ISR terminals. The space segment is composed of two interoperable satellite constellation rings (which can and probably will operate in other topologies than ring, e.g. mesh connectivity) and NASA as an edge service with compatible space and ground hardware. One of these two rings is for the Department of Defense (DoD) and another for the Intelligence Community (IC) backbone/relay. The terrestrial infrastructure segment includes interfaces to other DoD networks, teleports, NASA and National special purpose networks, and commercial systems and selected ground systems RF communications ground stations for uplink and downlink, and connection to the global information grid – bandwidth expansion (GIG-BE). Lastly, the network operations & management segment is the portion of the TCA that connects, where deemed appropriate, the ground networks of DoD, IC, and NASA managed by each entity and supports peering across these separately procured enclave systems so that resource sharing and fault tolerance can be supported in a system-of-systems sense. (GlobalSecurity.org, 2003)

The TCA will extend Internet-like services directly to warfighters, eliminating the need to use multi-hop satellite connections to reach Defense Information Switching Network (DISN) services through Standard Tactical Entry Point (STEP) sites located thousands of miles from the warfighters. The decreased latency and increased bandwidth of the TCA will deliver an order of magnitude increase in capacity compared to the current architecture.

A hierarchical addressing scheme with the geostationary (GEO) communications satellites acting as backbone routers has been proposed to route real-time traffic in the TCA. Low-earth orbit (LEO) satellites and the high-altitude platform (HAP) aircraft serve as second and third layer routers to provide high bandwidth with low latency for delay-sensitive transmissions. The footprints of the GEO satellites are divided into stationary cells on the earth to form one domain. Within that domain are smaller footprints from various LEO satellites, forming subdomains. Finally, HAP aircraft footprints further divide subdomains to complete the hierarchy. Since the GEO satellite footprints don't move, the key references for this topology are static. Using this addressing scheme, a static connection matrix is easily maintained and is used to determine routing. Figure 3 is a diagram the TCA (Durresi, and others, 2004:2).

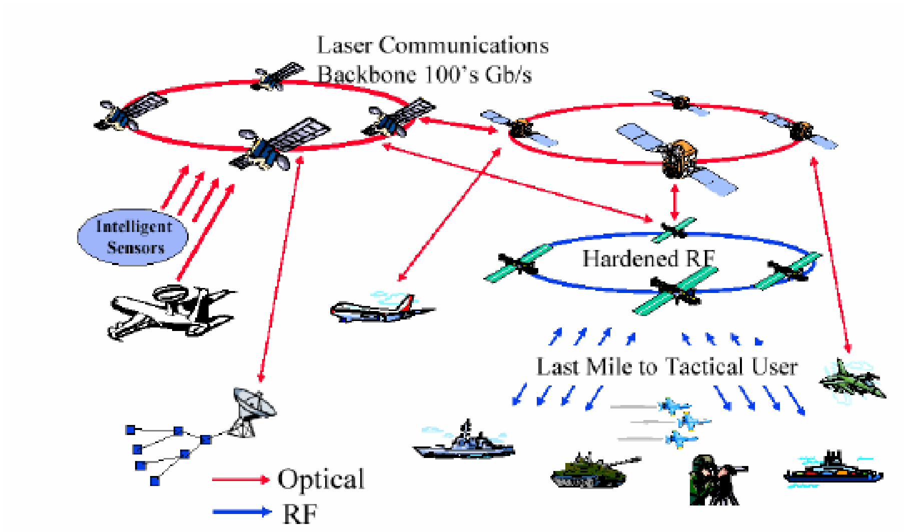

Figure 3. Transformational Communications Architecture (Durresi, 2004:2)

Communication can occur between nodes within any one of the three layers—GEO, LEO, or HAP. Communication can also be between any two of the three layers—GEO and LEO, GEO and HAP, or LEO and HAP. Finally, it considers communication between tactical users and either of the satellite layers—GEO or LEO. It does not address communication between the HAP layer and tactical users, and it does not consider the ability to reconfigure the network topology through the use of directional communications. Communication overhead for the TCA is decreased by dividing the network into domains using the GEO satellite footprints (Durresi, and others, 2004:16).

The Future

"Possibly the single-most transforming thing in our forces will not be a weapon system, but a set of interconnections and a substantially enhanced capability because of that awareness."

—Secretary of Defense Donald Rumsfeld, August 9, 2001.
(quoted in Meyerriecks, 2003)

In the future, seamless, interoperable, global connectivity will be attained. An Internet in the sky composed of hybrid communications capabilities will connect space, air, and ground nodes, eliminating the constraint communications currently puts on warfighters. Figure 4 shows a conceptual drawing of future connectivity.

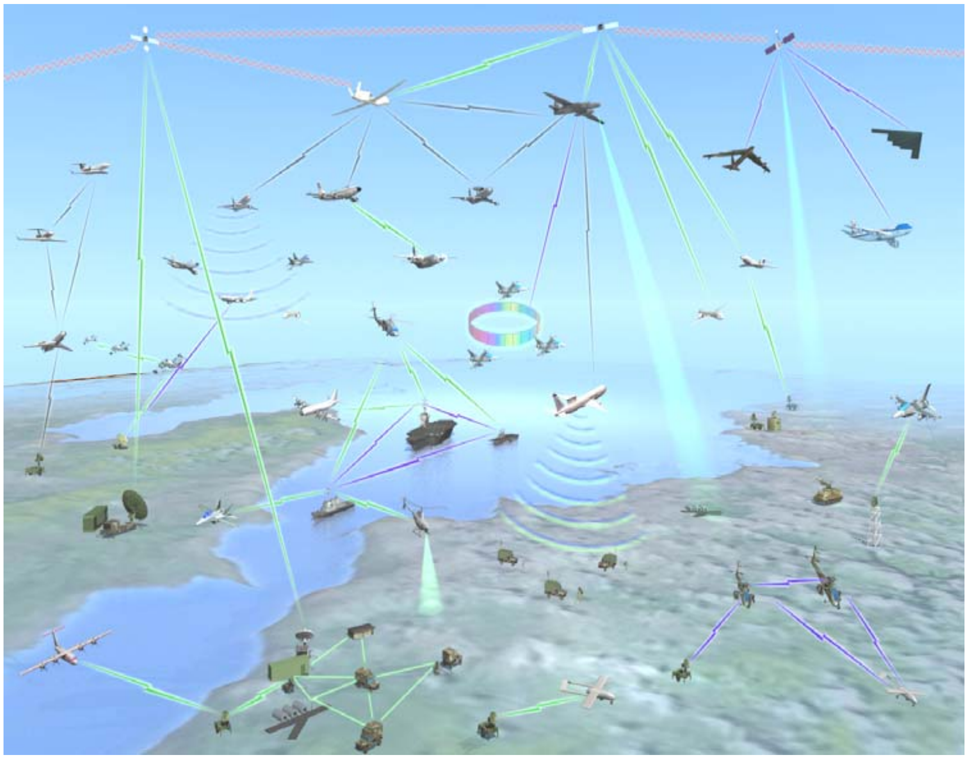

Figure 4. Future Connectivity (Hines, 2004:Slide 43)

The Way Ahead

There is a large separation between the realization of the future vision and current capability. Once the TCA infrastructure begins construction, bandwidth capacity will, most likely, come online incrementally. It is logical to assume bandwidth will be constrained for the immediate future. It is also logical to conclude priority access to available bandwidth will also be maintained.

Sender-Receiver Requirements.

Traffic on a network can be prioritized based on the requirements of the senders and receivers of the information. Military organizations, especially, have unique needs which are closely tied to mission requirements. For example, Special Operations Forces

(SOF) have unique characteristics which require their communications have a low probability of detection and a low probability of interception (LPD/LPI). They must also be able to operate covertly anywhere in the world. It is tempting to tailor current technology to meet SOF needs, but given the history with stovepipe systems, creating new families of specialized technology must be done with care.

Summary

The need to share information has led to the creation of tactical data networks where warfighters can share information rapidly. Unfortunately, unique functions and missions have also led to the creation of specialized, stovepipe systems which don't communicate with each other Advances in technology have led to a greater demand for immediate access to information with the Internet providing an example of how easy getting information can be. The current communications infrastructure cannot handle the demands and expectations that advances in technology are placing on it. Therefore, a TCA has been proposed to provide end-to-end connectivity, but debate about terminology and whether solutions developed for terrestrial networks apply. Military-specific needs might be better captured in an architecture based on the military characteristics.

III. Methodology

Chapter Overview

In this chapter the motivation and foundation for a framework to be used in the discussion and analysis of topological decision making within a TCA. An approach to characterizing user requirements and determining measures of cost and value associated with a given transmission. I will then describe a simulation scenario which represents an instantiation of a TCA, baseline its performance when using a standard routing algorithm and compare the results to the same topology using routing sensitive to our message context vector.

Characterizing Requirements

Organization affects thought. Conversely, thought affects organization. It is known that organizing communications based on functional lines leads to stovepiped systems and problems with interoperability. Starting from the position that information is more important than the system carrying it, a framework can be built which puts information needs at its core. Once the importance of information is established, the requirement must be specified in a language which includes relevant terminology. Finally, once the words and concepts to communicate with have been defined, formal reasoning can justify why any action should be taken and its impact on the overall ability to pass information.

One of the challenges of characterizing anything is deciding how to partition the space of interest. Communications requirements for military users are no exception.

There are several obvious ways one can partition that space; however, whenever possible, care must be taken so the partitioning doesn't introduce undesired long-term effects.

One obvious way to partition military communications is to divide the space up by organization. Since many organizations perform similar functions, this approach would require further division to reveal the core characteristics desired. Instead, by using a functional organizational hierarchy as the basis for characterizing communications, results more along the lines of what is desired emerge. Table 1 contains a characterization based on functional divisions.

Table 1. Characterization of Communications Based on Function

Functional Community	**Characterization of Communications**
Fighter	Real-time voice and data containing detailed threat and target information
Bomber	Real-time voice and data containing detailed target information
Reconnaissance	Secure, high-bandwidth data with time-critical targeting information
Medical	Time-sensitive life-saving data and administrative traffic
Command and Control	Extensive real-time secure voice and data with high bandwidth applications
Personnel	Mostly administrative traffic containing some sensitive information
Maintenance	Administrative traffic with time-sensitive logistical data

This approach begins with a characterization of each functional area followed by an iterative decomposition into parameters. When the list of parameters is fully decomposed, we should have a minimal set of parameters, or atomic properties, required to characterize our space; otherwise, we need to closely examine the parts of our space we can't characterize for synergy which we cannot accurately represent. For example, "secure" is important because it implies no adversary can get the information, which further implies either the information can't be detected, intercepted, or decrypted; and decryption implies both detection and interception. Hence, "detectibility" and "interceptibility" become two new parameters for characterizing communications in a TCA. A proposed list of new parameters, definitions, and examples are found in Table 2. Well-established measurable physical characteristics such as packet size, bandwidth, and propagation delay are not included in the list, but are still used as needed.

Table 2. Characterization of Communications Based on Parameters

Parameter	Definition	Example
Detectibility (link)	A measure of the likelihood that a transmission source will be detected by an adversary.	A laser link has low detectibility because its emissions are highly focused.
Interceptibility (message)	A measure of the likelihood that the contents of transmission will be captured by an adversary.	An unencrypted transmission using an omnidirectional RF antenna near an enemy territory has high interceptibility because an adversary is likely to both detect and read the information.
Perishability (message)	A measure of how long a transmission will be relevant.	A computer system update message has high perishability because current updates are provided several times every second.
Urgency (message)	A measure of how fast a transmission must reach its final destination in order to be useful.	An aircraft message stating that its status is "normal" has low urgency because the information will not trigger an action by the recipient.
Criticality (message)	A measure of the significance or impact of a transmission.	A message stating that a base is under attack is critical because it indicates a change in the threat level for an entire region.

The parameters above characterize communications in five dimensions. Thus, a class of messages is represented using a communications context vector composed of five variables describing message sensitivity to detectibility, interceptibility, perishability, urgency, and criticality. Similarly, links in a network are described using detectibility. Vectors for communications traffic and the network links may be compared to determine the propriety of a specific link for the class of message traffic being transmitted.

NS2 Simulator and Representing Message Requirements.

NS2 is a widely-accepted, open-source discrete event network simulator available from the University of Southern California's Information Sciences Institute at http://www.isi.edu/nsnam/ns/.

Each transmitted message in an instantiated TCA has its own requirements which are described using the communications parameters discussed earlier. To perform routing based on context, packet headers must contain the parameters necessary to capture the requirements for each individual packet.

This research is limited to one class of communications traffic per simulation scenario. The traffic class is described by two parameters—one capturing sensitivity to time delay and the other capturing sensitivity to signal detection. These parameters are referred to as "delay sensitivity" and "detectibility." Delay sensitivity is a hybrid parameter encapsulating the defined parameters "perishability" and "urgency." A hybrid parameter is used because perishability and urgency are not independent—both relate to time. Any amount of delay affects the cost associated with each parameter, potentially resulting in two different routing tables when either of their values changes. Since the simulator is limited to one routing table, delay sensitivity is used to indicate a value derived from a constant perishability and constant urgency.

To consider other classes of traffic, the values of the two parameters under consideration are changed to produce four classes, as shown in Table 3. The four classes are examined. Delay sensitivity and detectibility sensitivity are used in conjunction with parameters describing links to determine total costs which affect routing. The traffic classes are named according to their delay sensitivity-detectibility sensitivity pair, with "Low" representing the value 0.3 and "High" representing value 0.8. For example, the traffic class "High-Low" has delay sensitivity equal to 0.3 and detectibility sensitivity equal to 0.3.

Table 3. Simulation Scenarios

Traffic Class	Delay Sensitivity	Detectibility Sensitivity
Low-Low	0.3	0.3
Low-High	0.3	0.8
High-Low	0.8	0.3
High-High	0.8	0.8

Representing Network Ability to Meet Message Requirements. Message sensitivities describe what is important to each message in a class. Links are described using their detectibility. A link with high detectibility is emitting a detectible signal which an adversary may use to locate the transmitter. If a link is detectible, its likelihood of detection may have a direct relationship to the amount of time the link is active (transmitting). Table 4 gives some examples of how detectibility is represented. The table is not all-inclusive, and the detectibility numbers are notional. The simulations we use detectibility values of 0 and 1.

Table 4. Link Detectibility

Link Type	Detectibility	Rationale
Free-space optical laser	0.00	A narrow beam must hit detector directly to be detected.
Low-power, directional RF	0.20	Detector must lie in the same direction from the transmitter as the receiver and must be within range, or take advantage of inevitable side-lobe emissions.
High-power, directional RF	0.45	Detector must lie in the same direction from the transmitter as the receiver and can be at a greater range than the receiver, or take advantage of inevitable side-lobe emissions.
Low-power, omnidirectional RF	0.60	Detector can lie in any direction but and must be within range.
High-power, omnidirectional RF	0.85	Detector can lie in any direction but and can be at a greater range than the receiver.
High-power, multi-frequency, omnidirectional RF	0.95	Detection is possible from any direction at long range and on various frequencies.

Cost Function

Routing in the TCA is accomplished using a cost function based on parameters from messages and links. The cost associated with transmitting one packet from a specific message class across a specific link has two parts, Delay Cost and Detectibility Cost, and is defined as:

$$\text{Per Packet Cost} = \text{Delay Cost} + \text{Detectibility Cost}$$

where

$$\text{Delay Cost} = \text{Delay Sensitivity}*(\text{Packet Size}/\text{Bandwidth} + \text{Propagation Delay} + \text{Queuing Delay})$$

and

$$\text{Detectibility Cost} = \text{Detectibility Sensitivity} * (\text{Packet Size}/\text{Bandwidth})$$

Using the above cost equations, the total cost is calculated by summing the individual packet costs for each link a packet traverses. Bandwidth is used to compare the performance of the scenarios.

Simulation Model

The simulation models a TCA composed of 17 nodes described in Table 5. Each satellite has only laser-optical links, while the remaining nodes have either a single link or a combination or laser-optical and RF links. The "Detectible" column in Appendix A, Table 10 indicates whether or not the links in the TCA are detectible.

Table 5. Simulated Transformational Communication Architecture

Layer	Description	Nodes	Example
GEO	Geostationary Satellites	0,1,2	Wide-area Communications Satellites
LEO	Low-Earth Orbit Satellites	3,4,5	Regional Communications Satellites
HAP	High-Altitude Platforms	6,7	High-Altitude Aircraft with long loitering times
LAP	Low-Altitude Platforms	8,9,10,11	Remotely-Piloted or Unmanned Aerial Vehicles (UAV)
GLP	Ground-Layer Platforms	12,13,14,15,16	Military Bases

All layers can communicate with adjacent layers. All nodes, except for GLP nodes, can communicate within their own layer. TCA topology is shown in Figure 5. Node 0 represents "reach back" connectivity to distant locations, such as from a theater of operations back to the continental U.S. Node 0 has a longer delay due to the greater distance involved.

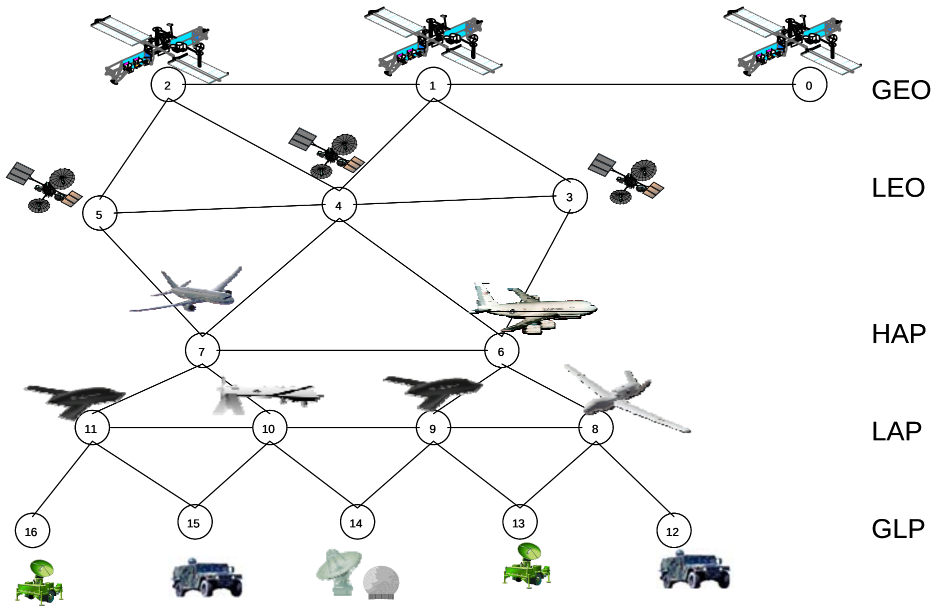

Figure 5. Simulation TCA Topology

Simulation Message Transmissions

A message set was chosen to represent the types of traffic one might see during real-world military operation. It includes communications between various nodes traveling across links in both directions. The transmissions arrive according to a Poisson process with packet size of 1000 bytes. There are 17 transmissions between 9 source-destination pairs, as shown in Table 6. The amount of data transmitted from each node is designed to approximate classes of military data including intelligence imagery, intelligence messages, UAV video, UAV command and control, diplomatic communications, general command and control, status reports, medical diagnostic, and general mission-related traffic. The same transmission set characteristics are used for all simulation runs.

Table 6. Message Transmissions

Source Node	Destination Node	Offered Load (Kbits/sec)
0	12	16.0
	14	10.0
	15	11.4
7	6	20.0
	13	11.4
	15	11.4
8	13	26.7
9	13	26.7
12	0	80.0
	0	80.0
13	0	80.0
	8	40.0
	9	40.0
14	15	80.0
15	0	26.7
16	6	22.9
	7	22.9

Baseline Simulation

The baseline simulation scenario uses NS2's implementation of Dijkstra's All-Pairs Shortest Path Routing Algorithm to compute the traffic routes for the TCA. Simulation statistics on the number of packets flowing over each link are collected for the message set described earlier. The cost function calculates the total cost that would have resulted using the routing table computed by Dijkstra's algorithm for each of the four test cases. This data is compared to the results obtained from using the context-based routing.

Scenarios

Four scenarios are specified in Table 3 for Low-Low, Low-High, High-Low, and High-High parameters. Using these parameters and the cost function, costs are computed and context-based routing table is built for each test case. Simulations are run with each of the four new routing tables and the number of packets flowing over each link are recorded. Total cost associated with each new routing table is computed and compared with the cost the new packet flows would have incurred using the costs associated with the routing from the baseline..

Summary

This chapter described the terminology and cost and value functions used our TCA framework. It detailed the topology and test cases used to simulate the TCA, as well as a general procedure for the comparisons that are accomplished in the upcoming analysis.

IV. Analysis and Results

Chapter Overview

The new framework for routing and decision-making within a TCA showed an improvement over Dijkstra's algorithm in selecting routes based on message requirements. Compared to the baseline, cost improved for all of the test cases, while performance improved slightly in one case.

Results of Simulation Scenarios

NS2 computed the best routes using Dijkstra's algorithm. By counting the number of packets that flowed over each link in the topology, the costs that would have incurred had these same packets been assigned context parameters. The packet flows and cost comparison using the baseline data are captured in Table 7. Additional calculations may be found in Appendix A. In calculating the cost, the number of packets traversing each link remained constant. The two parameters weighted each component of cost differently, resulting in the different totals found at the bottom of the table.

Table 7. Baseline Packet Flows and Costs

From Node	To Node	Dijkstra Packets	Low-Low Per Packet Cost	Low-Low Dijkstra Cost	Low-Low Per Packet Cost	Low-High Dijkstra Cost	High-Low Per Packet Cost	High-Low Dijkstra Cost	High-High Per Packet Cost	High-High Dijkstra Cost
0	1	2574	0.0371	95.52	0.0371	95.52	0.0990	254.72	0.0990	254.72
1	0	5359	0.0371	198.87	0.0371	198.87	0.0990	530.33	0.0990	530.33
1	2	0	0.0016	0.00	0.0016	0.00	0.0043	0.00	0.0043	0.00
1	3	1831	0.0355	64.98	0.0355	64.98	0.0946	173.29	0.0946	173.29
1	4	743	0.0355	26.37	0.0355	26.37	0.0946	70.32	0.0946	70.32
2	1	0	0.0016	0.00	0.0016	0.00	0.0043	0.00	0.0043	0.00
2	4	0	0.0355	0.00	0.0355	0.00	0.0946	0.00	0.0946	0.00
2	5	0	0.0355	0.00	0.0355	0.00	0.0946	0.00	0.0946	0.00
3	1	4490	0.0355	159.35	0.0355	159.35	0.0946	424.94	0.0946	424.94
3	4	0	0.0005	0.00	0.0005	0.00	0.0013	0.00	0.0013	0.00
3	6	1831	0.0005	0.88	0.0005	0.88	0.0013	2.36	0.0013	2.36
4	1	869	0.0355	30.84	0.0355	30.84	0.0946	82.24	0.0946	82.24
4	2	0	0.0355	0.00	0.0355	0.00	0.0946	0.00	0.0946	0.00
4	3	0	0.0005	0.00	0.0005	0.00	0.0013	0.00	0.0013	0.00
4	5	0	0.0005	0.00	0.0005	0.00	0.0013	0.00	0.0013	0.00
4	6	0	0.0005	0.00	0.0005	0.00	0.0013	0.00	0.0013	0.00
4	7	743	0.0005	0.36	0.0005	0.36	0.0013	0.96	0.0013	0.96
5	2	0	0.0355	0.00	0.0355	0.00	0.0946	0.00	0.0946	0.00
5	4	0	0.0005	0.00	0.0005	0.00	0.0013	0.00	0.0013	0.00
5	7	0	0.0005	0.00	0.0005	0.00	0.0013	0.00	0.0013	0.00
6	3	4490	0.0005	2.17	0.0005	2.17	0.0013	5.78	0.0013	5.78
6	4	0	0.0005	0.00	0.0005	0.00	0.0013	0.00	0.0013	0.00
6	7	0	0.0003	0.00	0.0004	0.00	0.0009	0.00	0.0009	0.00
6	8	2138	0.0010	2.05	0.0018	3.76	0.0018	3.76	0.0026	5.47
6	9	785	0.0005	0.38	0.0005	0.38	0.0013	1.00	0.0013	1.00
7	4	869	0.0005	0.42	0.0005	0.42	0.0013	1.12	0.0013	1.12
7	5	0	0.0005	0.00	0.0005	0.00	0.0013	0.00	0.0013	0.00
7	6	2999	0.0003	1.04	0.0004	1.09	0.0009	2.74	0.0009	2.78
7	10	1469	0.0010	1.41	0.0018	2.59	0.0018	2.59	0.0026	3.76
7	11	0	0.0005	0.00	0.0005	0.00	0.0013	0.00	0.0013	0.00
8	6	4490	0.0010	4.31	0.0018	7.90	0.0018	7.90	0.0026	11.49
8	9	0	0.0011	0.00	0.0019	0.00	0.0022	0.00	0.0030	0.00
8	12	1046	0.0012	1.26	0.0012	1.26	0.0032	3.35	0.0032	3.35
8	13	2272	0.0024	5.45	0.0044	10.00	0.0044	10.00	0.0064	14.54
9	6	0	0.0005	0.00	0.0005	0.00	0.0013	0.00	0.0013	0.00
9	8	0	0.0011	0.00	0.0019	0.00	0.0022	0.00	0.0030	0.00
9	10	0	0.0011	0.00	0.0019	0.00	0.0022	0.00	0.0030	0.00
9	13	951	0.0012	1.14	0.0012	1.14	0.0032	3.04	0.0032	3.04
9	14	785	0.0024	1.88	0.0044	3.45	0.0044	3.45	0.0064	5.02
10	7	869	0.0010	0.83	0.0018	1.53	0.0018	1.53	0.0026	2.22
10	9	0	0.0011	0.00	0.0019	0.00	0.0022	0.00	0.0030	0.00
10	11	0	0.0011	0.00	0.0019	0.00	0.0022	0.00	0.0030	0.00
10	14	0	0.0012	0.00	0.0012	0.00	0.0032	0.00	0.0032	0.00
10	15	3023	0.0024	7.26	0.0044	13.30	0.0044	13.30	0.0064	19.35
11	7	2238	0.0005	1.07	0.0005	1.07	0.0013	2.86	0.0013	2.86
11	10	0	0.0011	0.00	0.0019	0.00	0.0022	0.00	0.0030	0.00
11	15	0	0.0012	0.00	0.0012	0.00	0.0032	0.00	0.0032	0.00
11	16	0	0.0024	0.00	0.0044	0.00	0.0044	0.00	0.0064	0.00
12	8	3032	0.0012	3.64	0.0012	3.64	0.0032	9.70	0.0032	9.70
13	8	2857	0.0024	6.86	0.0044	12.57	0.0044	12.57	0.0064	18.28
13	9	1291	0.0012	1.55	0.0012	1.55	0.0032	4.13	0.0032	4.13
14	9	0	0.0024	0.00	0.0044	0.00	0.0044	0.00	0.0064	0.00
14	10	1554	0.0012	1.86	0.0012	1.86	0.0032	4.97	0.0032	4.97
15	10	869	0.0024	2.09	0.0044	3.82	0.0044	3.82	0.0064	5.56
15	11	0	0.0012	0.00	0.0012	0.00	0.0032	0.00	0.0032	0.00
16	11	2238	0.0024	5.37	0.0044	9.85	0.0044	9.85	0.0064	14.32
TOTALS		58705		629.22		660.53		1646.62		1677.92

The cost values for the Low-Low scenario which are contained in the "Low-Low Dijkstra Cost" column in Table 7 were assigned to the topology to construct the diagram in Figure 6. The baseline routing table in Figure 7 was computed using Dijkstra's algorithm and mapped the path from Node 0 to Node 12. The shaded cells indicate links that packets flowed across in the baseline scenario. These nodes were used to start because it was known that there was a message from Node 0 to Node 12. The Dijkstra route was superimposed on top of the link cost diagram and visually inspected the alternatives to find a minimal span.

In general, it is easy to find a minimum spanning tree for any given network, but the problem becomes much more challenging as the number of routing criteria grows beyond one-dimensional values like hop-count or delay. A minimum spanning tree can still be found if the traffic is specified along with all criteria for all flows in the network, at the price of additional computation, but it is far more difficult to find a general answer for any traffic pattern than it is in traditional networks. Instead, a simple visual inspection of the links for the route with cheaper cost was done. One was found and the process was repeated for all message traffic to create the new routing table in Figure 8. The shaded cells in the context-based routing tables indicate routes different from Dijkstra's baseline routing table. The context-based routing tables for the other three scenarios were computed in the same manner. The remaining routing tables may be found in Appendix A.

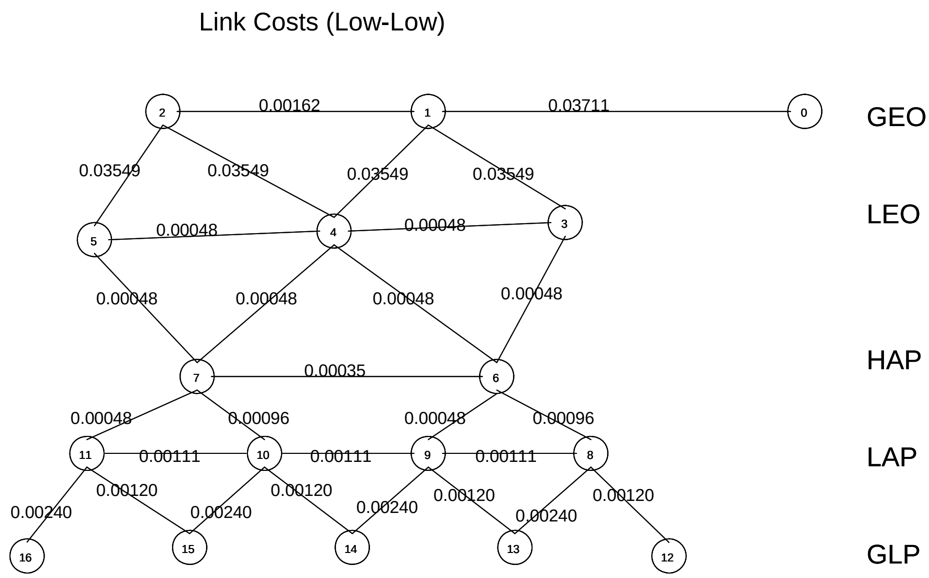

Figure 6. Low-Low Scenario Link Costs

Dijkstra's All-pairs SPF Algorithim

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	--	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	0	--	2	3	4	2	3	4	3	3	4	4	3	3	3	4	4
2	1	1	--	1	4	5	4	4	4	4	4	4	4	4	4	4	4
3	1	1	1	--	4	4	6	4	6	6	4	4	6	6	6	4	4
4	1	1	2	3	--	5	6	7	6	6	7	7	6	6	6	7	7
5	2	2	2	4	4	--	4	7	4	4	7	7	4	4	7	7	7
6	3	3	4	3	4	4	--	7	8	9	7	7	8	8	9	7	7
7	4	4	4	4	4	5	6	--	6	6	10	11	6	6	10	10	11
8	6	6	6	6	6	6	6	6	--	9	9	6	12	13	9	9	6
9	6	6	6	6	6	6	6	6	8	--	10	10	8	13	14	10	10
10	7	7	7	7	7	7	7	7	9	9	--	11	9	9	14	15	11
11	7	7	7	7	7	7	7	7	7	10	10	--	7	10	10	15	16
12	8	8	8	8	8	8	8	8	8	8	8	8	--	8	8	8	8
13	8	8	8	8	8	8	8	8	8	9	9	9	8	--	9	9	9
14	9	9	9	9	9	10	9	10	9	9	10	10	9	9	--	10	10
15	10	10	10	10	10	10	10	10	10	10	10	11	10	10	10	--	11
16	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	--

Figure 7. Baseline Routing Table

Context-based Routing (Low-Low)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	--	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	0	--	2	3	4	2	3	4	3	3	4	4	3	3	4	4	4
2	1	1	--	1	4	5	4	4	4	4	4	4	4	4	4	4	4
3	1	1	1	--	4	4	6	4	6	6	4	4	6	6	6	4	4
4	1	1	2	3	--	5	6	7	6	6	7	7	6	6	7	7	7
5	2	2	2	4	4	--	4	7	4	4	7	7	4	4	7	7	7
6	3	3	4	3	4	4	--	7	8	9	7	7	8	9	9	7	7
7	4	4	4	4	4	5	6	--	6	6	10	11	6	6	11	11	11
8	6	6	6	6	6	6	6	6	--	9	9	6	12	9	9	9	6
9	6	6	6	6	6	6	6	6	8	--	10	10	8	13	14	10	10
10	7	7	7	7	7	7	7	7	9	9	--	11	9	9	14	11	11
11	7	7	7	7	7	7	7	7	7	10	10	--	7	10	10	15	16
12	8	8	8	8	8	8	8	8	8	8	8	8	--	8	8	8	8
13	9	8	8	8	8	8	8	8	9	9	9	9	8	--	9	9	9
14	9	9	9	9	9	10	9	10	9	9	10	10	9	9	--	10	10
15	11	10	10	10	10	10	10	10	10	10	10	11	10	10	10	--	11
16	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	--

Figure 8. Low-Low Scenario Context-Based Routing Table

The context-based routing tables were used to reprogram the routes used by the simulator and the simulations were rerun for each scenario. The new packet flows and the costs associated with each scenario are recorded Table 8. New packet routes resulted in a different number of packets flowing over each link and the new costs listed in the table.

Table 8. Scenario Packet Flows and Costs

From Node	To Node	Low-Low Packets	Per Packet Cost	Low-Low Cost	Low-High Packets	Per Packet Cost	Low-High Cost	High-Low Packets	Per Packet Cost	High-Low Cost	High-High Packets	Per Packet Cost	High-High Cost
0	1	2574	0.0371	95.52	2574	0.0371	95.52	2574	0.0990	254.72	2574	0.0990	254.72
1	0	5196	0.0371	192.82	5196	0.0371	192.82	5359	0.0990	530.33	5196	0.0990	514.20
1	2	0	0.0016	0.00	0	0.0016	0.00	0	0.0043	0.00	0	0.0043	0.00
1	3	1046	0.0355	37.12	1046	0.0355	37.12	1046	0.0946	98.99	1046	0.0946	98.99
1	4	1528	0.0355	54.23	1528	0.0355	54.23	1528	0.0946	144.61	1528	0.0946	144.61
2	1	0	0.0016	0.00	0	0.0016	0.00	0	0.0043	0.00	0	0.0043	0.00
2	4	0	0.0355	0.00	0	0.0355	0.00	0	0.0946	0.00	0	0.0946	0.00
2	5	0	0.0355	0.00	0	0.0355	0.00	0	0.0946	0.00	0	0.0946	0.00
3	1	4327	0.0355	153.57	4327	0.0355	153.57	4490	0.0946	424.94	4327	0.0946	409.51
3	4	0	0.0005	0.00	0	0.0005	0.00	0	0.0013	0.00	0	0.0013	0.00
3	6	1046	0.0005	0.50	1046	0.0005	0.50	1046	0.0013	1.35	1046	0.0013	1.35
4	1	869	0.0355	30.84	869	0.0355	30.84	869	0.0946	82.24	869	0.0946	82.24
4	2	0	0.0355	0.00	0	0.0355	0.00	0	0.0946	0.00	0	0.0946	0.00
4	3	0	0.0005	0.00	0	0.0005	0.00	0	0.0013	0.00	0	0.0013	0.00
4	5	0	0.0005	0.00	0	0.0005	0.00	0	0.0013	0.00	0	0.0013	0.00
4	6	0	0.0005	0.00	0	0.0005	0.00	0	0.0013	0.00	0	0.0013	0.00
4	7	1528	0.0005	0.74	1528	0.0005	0.74	1528	0.0013	1.97	1528	0.0013	1.97
5	2	0	0.0355	0.00	0	0.0355	0.00	0	0.0946	0.00	0	0.0946	0.00
5	4	0	0.0005	0.00	0	0.0005	0.00	0	0.0013	0.00	0	0.0013	0.00
5	7	0	0.0005	0.00	0	0.0005	0.00	0	0.0013	0.00	0	0.0013	0.00
6	3	4327	0.0005	2.09	4327	0.0005	2.09	4490	0.0013	5.78	4327	0.0013	5.57
6	4	0	0.0005	0.00	0	0.0005	0.00	0	0.0013	0.00	0	0.0013	0.00
6	7	0	0.0003	0.00	0	0.0004	0.00	0	0.0009	0.00	0	0.0009	0.00
6	8	1046	0.0010	1.00	1046	0.0018	1.84	1046	0.0018	1.84	1046	0.0026	2.68
6	9	1092	0.0005	0.52	1092	0.0005	0.52	1092	0.0013	1.40	1092	0.0013	1.40
7	4	869	0.0005	0.42	869	0.0005	0.42	869	0.0013	1.12	869	0.0013	1.12
7	5	0	0.0005	0.00	0	0.0005	0.00	0	0.0013	0.00	0	0.0013	0.00
7	6	2999	0.0003	1.04	2999	0.0004	1.09	2999	0.0009	2.74	2999	0.0009	2.78
7	10	0	0.0010	0.00	785	0.0018	1.38	785	0.0018	1.38	0	0.0026	0.00
7	11	2254	0.0005	1.08	1469	0.0005	0.71	1469	0.0013	1.88	2254	0.0013	2.89
8	6	3032	0.0010	2.91	3032	0.0018	5.34	3032	0.0018	5.34	3032	0.0026	7.76
8	9	1180	0.0011	1.31	1180	0.0019	2.25	0	0.0022	0.00	1180	0.0030	3.49
8	12	1046	0.0012	1.26	1046	0.0012	1.26	1046	0.0032	3.35	1046	0.0032	3.35
8	13	0	0.0024	0.00	0	0.0044	0.00	1180	0.0044	5.19	0	0.0064	0.00
9	6	1295	0.0005	0.62	1295	0.0005	0.62	1458	0.0013	1.87	1295	0.0013	1.66
9	8	1092	0.0011	1.21	1092	0.0019	2.09	0	0.0022	0.00	1092	0.0030	3.23
9	10	0	0.0011	0.00	0	0.0019	0.00	0	0.0022	0.00	0	0.0030	0.00
9	13	3223	0.0012	3.87	3223	0.0012	3.87	2043	0.0032	6.54	3223	0.0032	10.31
9	14	0	0.0024	0.00	0	0.0044	0.00	0	0.0044	0.00	0	0.0064	0.00
10	7	0	0.0010	0.00	0	0.0018	0.00	0	0.0018	0.00	0	0.0026	0.00
10	9	0	0.0011	0.00	0	0.0019	0.00	0	0.0022	0.00	0	0.0030	0.00
10	11	1554	0.0011	1.72	1554	0.0019	2.97	0	0.0022	0.00	1554	0.0030	4.60
10	14	785	0.0012	0.94	785	0.0012	0.94	785	0.0032	2.51	785	0.0032	2.51
10	15	0	0.0024	0.00	0	0.0044	0.00	1554	0.0044	6.84	0	0.0064	0.00
11	7	3107	0.0005	1.49	3107	0.0005	1.49	3107	0.0013	3.98	3107	0.0013	3.98
11	10	785	0.0011	0.87	0	0.0019	0.00	0	0.0022	0.00	785	0.0030	2.32
11	15	3023	0.0012	3.63	3023	0.0012	3.63	1469	0.0032	4.70	3023	0.0032	9.67
11	16	0	0.0024	0.00	0	0.0044	0.00	0	0.0044	0.00	0	0.0064	0.00
12	8	3032	0.0012	3.64	3032	0.0012	3.64	3032	0.0032	9.70	3032	0.0032	9.70
13	8	0	0.0024	0.00	0	0.0044	0.00	1399	0.0044	6.16	0	0.0064	0.00
13	9	4148	0.0012	4.98	4148	0.0012	4.98	2749	0.0032	8.80	4148	0.0032	13.27
14	9	0	0.0024	0.00	0	0.0044	0.00	0	0.0044	0.00	0	0.0064	0.00
14	10	1554	0.0012	1.86	1554	0.0012	1.86	1554	0.0032	4.97	1554	0.0032	4.97
15	10	0	0.0024	0.00	0	0.0044	0.00	0	0.0044	0.00	0	0.0064	0.00
15	11	869	0.0012	1.04	869	0.0012	1.04	869	0.0032	2.78	869	0.0032	2.78
16	11	2238	0.0024	5.37	2238	0.0044	9.85	2238	0.0044	9.85	2238	0.0064	14.32
TOTALS		62664		608.24	61879		619.21	58705		1637.84	62664		1621.96

The motivation for creating our scenario was to perform system-level performance analysis. By focusing on the total number of packets and not their timings, variations have been effectively eliminated from the simulation analysis. The Poisson process used to generate the packets creates an expected number of packets and distributes them over a time interval. Since we combine all intervals to get our packet count, we get the original number simulator started with—it is deterministic and doesn't change no matter how often we run the simulation. Future work will not be limited to a single class of traffic, so variations in packet sizes, routing tables, and context parameters will enable a more extensive analysis.

Investigative Questions Answered

According to the cost metric derived earlier, the new routing outperforms Dijkstra's. This is to be expected as these costs are not considered in Dijkstra's algorithm. When context-based routes were used, packet flows through the system increased and cost decreased, as indicated in Table 9. The context-based routes were better suited to meet the needs of the message traffic flowing through the network. Increases in the number of packets traversing links are a direct result of the attempt to achieve lower cost by routing packets differently. However, since our cost equation uses link bandwidth in the denominator of both the detectibility and delay contributions to cost, it is reasonable to expect that an increase in system bandwidth would accompany a lower overall cost. More detailed simulation and analysis is needed to make that determination.

Table 9. Comparison of Context-Based and Dijkstra Packets and Costs

	Dijkstra Packets	Low-Low Packets	Low-Low Cost	Low-HIgh Packets	Low-High Cost	High-Low Packets	High-Low Cost	High-High Packets	High-High Cost
Dijkstra	58705		629.22		660.53		1646.62		1677.92
Context-Based		62664	608.24	61879	619.21	58705	1637.84	62664	1621.96
% Improvement over Dijkstra		6.74%	3.34%	5.41%	6.25%	0.00%	0.53%	6.74%	3.34%

Since the cost function is based on a linear function of the parameters for sensitivities to delay and detection, the corresponding packet count and cost values for any two scenarios where the sensitivities to delay and detection are equal should be the same. Results for the Low-Low and High-High scenarios confirm this.

Local cost is partially dependent on link bandwidth, but the relationship between total cost and system bandwidth has not been determined. Figure 9 shows the bandwidth comparison between the Dijkstra baseline and the Low-Low scenario. The Dijkstra baseline experienced a higher effective bandwidth throughout most of the simulation, resulting in the Low-Low scenario having a 4.68% system bandwidth improvement over the Dijkstra baseline. The bandwidth calculations and remaining bandwidth loss scenario figures are included in Appendix A. The system bandwidth is summarized in Table 10, which shows an improvement for only one of the four scenarios.

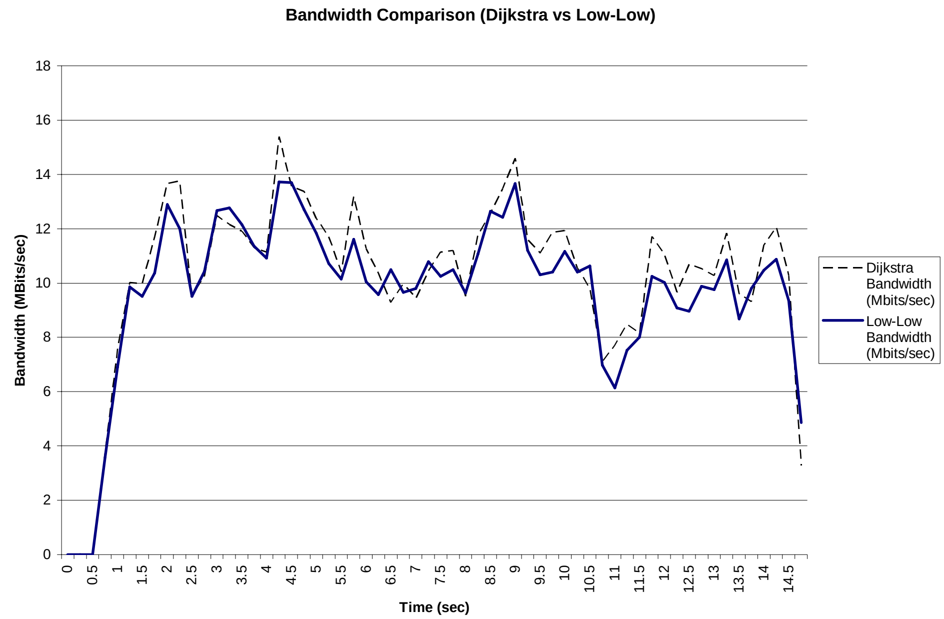

Figure 9. Bandwidth (Dijkstra vs Low-Low)

The High-Low scenario was the only one which showed a system bandwidth improvement over the Dijkstra baseline. Once again, the Low-Low and High-High scenarios were duplicate images of each other. The Low-Low, Low-High, and High-High scenarios each showed a 4.68% decrease in effective system bandwidth compared to the Dijkstra baseline. This decrease was calculated by averaging each scenario's bandwidth over the 60 time intervals and comparing them to the average from the Dijkstra baseline. Our new routings adversely affected overall system performance in most cases. The interesting case is the High-Low scenario which showed a 0.56% system bandwidth increase. There was also an accompanying cost improvement for this scenario. Since cost improved in all cases and bandwidth improved in only one case, the results suggest that we don't have enough information to correlate the two. The nonrandom nature of our traffic load clouds the meaning of the changes in system bandwidth. The routing table for the High-Low scenario in Appendix A, Figure 14, indicates that additional links are traversed in some cases because the high sensitivity to detection wants to achieve a lower cost, not necessarily a lower hop count. The additional hops may relieve congestion at adjacent nodes, resulting in the increased bandwidth.

Summary

The Dijkstra baseline scenario was used to project routes more suitable to our message sensitivities. As expected, the new context-based routes showed across-the-board improvements in cost. Packet flows were at least as high as the Dijkstra baseline for every scenario, and system bandwidth improved in one case. While improved costs were directly related to our routing changes, the bandwidth improvement may have been caused by other factors.

Table 10. System Bandwidth Summary

Time (sec)	Dijkstra Bandwidth (Mbits/sec)	Low-Low Bandwidth (Mbits/sec)	Low-High Bandwidth (Mbits/sec)	High-Low Bandwidth (Mbits/sec)	High-High Bandwidth (Mbits/sec)
0	0	0	0	0	0
0.25	0	0	0	0	0
0.5	0	0	0	0	0
0.75	3.744	3.584	3.584	3.744	3.584
1	7.584	6.912	6.912	7.968	6.912
1.25	10.016	9.856	9.856	10.848	9.856
1.5	9.984	9.504	9.504	9.312	9.504
1.75	11.712	10.368	10.368	11.232	10.368
2	13.664	12.896	12.896	13.92	12.896
2.25	13.76	12	12	13.472	12
2.5	9.536	9.504	9.504	9.536	9.504
2.75	10.24	10.432	10.464	10.24	10.432
3	12.48	12.672	12.64	12.448	12.672
3.25	12.16	12.768	12.768	12.128	12.768
3.5	11.904	12.16	12.16	11.936	12.16
3.75	11.296	11.36	11.392	11.68	11.36
4	11.136	10.912	10.88	12.096	10.912
4.25	15.392	13.728	13.728	15.392	13.728
4.5	13.568	13.696	13.696	14.112	13.696
4.75	13.376	12.704	12.736	13.536	12.704
5	12.384	11.84	11.808	11.36	11.84
5.25	11.712	10.72	10.72	11.264	10.72
5.5	10.4	10.144	10.144	10.464	10.144
5.75	13.184	11.616	11.616	13.184	11.616
6	11.264	10.048	10.048	11.232	10.048
6.25	10.368	9.568	9.568	10.4	9.568
6.5	9.28	10.496	10.496	9.28	10.496
6.75	9.952	9.664	9.664	9.984	9.664
7	9.44	9.792	9.792	9.376	9.792
7.25	10.432	10.784	10.784	10.432	10.784
7.5	11.136	10.24	10.272	12.096	10.24
7.75	11.2	10.496	10.464	11.776	10.496
8	9.504	9.632	9.632	8.8	9.632
8.25	11.776	11.072	11.072	11.168	11.072
8.5	12.576	12.64	12.64	12.992	12.64
8.75	13.472	12.416	12.416	13.792	12.416
9	14.592	13.664	13.696	15.616	13.664
9.25	11.584	11.2	11.168	12.416	11.2
9.5	11.104	10.304	10.304	11.936	10.304
9.75	11.872	10.4	10.4	12.576	10.4
10	11.936	11.168	11.168	11.904	11.168
10.25	10.56	10.4	10.4	10.496	10.4
10.5	9.792	10.624	10.624	8.448	10.624
10.75	7.104	6.976	6.976	6.976	6.976
11	7.712	6.144	6.144	7.744	6.144
11.25	8.48	7.52	7.52	8.512	7.52
11.5	8.16	8	8	8.128	8
11.75	11.712	10.24	10.24	11.712	10.24
12	11.04	10.016	10.016	11.168	10.016
12.25	9.664	9.088	9.12	9.536	9.088
12.5	10.688	8.96	8.928	10.688	8.96
12.75	10.528	9.888	9.888	10.56	9.888
13	10.272	9.76	9.76	10.272	9.76
13.25	11.84	10.848	10.848	11.808	10.848
13.5	9.6	8.672	8.672	9.6	8.672
13.75	9.312	9.792	9.792	9.312	9.792
14	11.392	10.464	10.464	11.36	10.464
14.25	12.064	10.88	10.88	12.064	10.88
14.5	10.272	9.344	9.344	10.304	9.344
14.75	3.296	4.864	4.864	3.296	4.864
Cumulative Bandwidth	614.208	585.44	585.44	617.632	585.44
Avg bandwidth per time interval (Mbits/sec)	10.24	9.76	9.76	10.29	9.76
% Increase/Decrease compared to Dijkstra	N/A	-4.68%	-4.68%	0.56%	-4.68%

V. Conclusions and Recommendations

Chapter Overview

In this chapter the research conclusions and their significance is presented. Recommendations for future work are discussed.

Conclusions of Research

Terminology for five new communications parameters was successfully created to better identify military communications requirements. The new terminology is able to describe military requirements in terms more relevant than was possible before with standard computer communications network terminology. A routing cost function was devised with the new terminology and successfully routed packets through the TCA in a manner more consistent with user needs than was observed when using Dijkstra's All-Pairs Shortest Path routing algorithm.

Significance of Research

This research provides a more suitable approach for representing user requirements and more effectively addresses warfighter needs. New terminology created by this research allows routing paths tailored to user-approved context of each individual packet. This capability could result in the better utilization of limited resources such as hard-to-detect laser links. Also, since the TCA and terminology can account for link types, it now becomes feasible to reconfigure the TCA topology based on user requirements in conjunction with network performance, not just performance alone.

Recommendations for Future Research

This thesis provides an initial look at defining terminology which will allow us to more appropriately define user requirements and potentially take greater advantage of the capabilities of a TCA. A more in-depth analysis is needed in order to better understand the implications. Our recommendations for future research include:

- Re-examine the communications terminology and modify the parameter definitions to make them all mathematically independent of each other. This should help improve understanding of how each parameter affects performance.

- Build a new cost function based on all of the communications parameters and use it in conjunction with an updated simulator which has been modified to route packets based on the parameter values. Include random packet sources and destinations to eliminate dependencies on deterministic traffic flows from the results. This will provide a more realistic simulation for the TCA.

- Incorporate the Downhill Simplex Method in Multidimensions algorithm into the packet routing logic of the simulator to find the minimum cost of a function of more than one independent variable (Press, and others, 1992:408). Investigate how the algorithm might be used offline to identify the best routes for all packet types traveling from any node to any other node.

- Investigate how a "Communications Tasking Order" might be created automatically to direct slewable TCA links to change the network topology in order to achieve a desired effect.

Summary

This research presents a framework for routing and topological decision-making within a Transformational Communications Architecture. Five terms were presented to more precisely capture user requirements. Two of the terms were used to create a packet routing cost function and a simulation was conducted to show the feasibility of the approach. The cost function resulted in packet routing which more closely matched user requirements and improved system performance under most scenarios. The relationship between system performance and the cost function could not be clearly determined.

Finally, recommendations for future, related research efforts were proposed.

Appendix A. Related Data and Calculations

Table 11. Calculation of Low-Low Scenario Total Cost Per Packet

0.3 Delay Sensitivity
0.3 Detectibility
1000 Packet Size (bytes)

This table is used to calculate costs using the routes from Dijkstra's All-Pairs algorithm.
These costs are used to calculate better (lower cost) routes based on context.

From Node	To Node	Bandwidth (bps)	Detectible 0 = No 1 = Yes	Propagation + Queue Delay (sec)	Delay Sensitivity Cost	Detectibility Cost	Total Cost Per Packet
0	1	10000000000	0	0.12370	0.03711	0.00000	0.03711
1	0	10000000000	0	0.12370	0.03711	0.00000	0.03711
1	2	10000000000	0	0.00540	0.00162	0.00000	0.00162
1	3	10000000000	0	0.11830	0.03549	0.00000	0.03549
1	4	10000000000	0	0.11830	0.03549	0.00000	0.03549
2	1	10000000000	0	0.00540	0.00162	0.00000	0.00162
2	4	10000000000	0	0.11830	0.03549	0.00000	0.03549
2	5	10000000000	0	0.11830	0.03549	0.00000	0.03549
3	1	10000000000	0	0.11830	0.03549	0.00000	0.03549
3	4	10000000000	0	0.00160	0.00048	0.00000	0.00048
3	6	1000000000	0	0.00160	0.00048	0.00000	0.00048
4	1	10000000000	0	0.11830	0.03549	0.00000	0.03549
4	2	10000000000	0	0.11830	0.03549	0.00000	0.03549
4	3	10000000000	0	0.00160	0.00048	0.00000	0.00048
4	5	10000000000	0	0.00160	0.00048	0.00000	0.00048
4	6	1000000000	0	0.00160	0.00048	0.00000	0.00048
4	7	1000000000	0	0.00160	0.00048	0.00000	0.00048
5	2	10000000000	0	0.11830	0.03549	0.00000	0.03549
5	4	10000000000	0	0.00160	0.00048	0.00000	0.00048
5	7	1000000000	0	0.00160	0.00048	0.00000	0.00048
6	3	1000000000	0	0.00160	0.00048	0.00000	0.00048
6	4	1000000000	0	0.00160	0.00048	0.00000	0.00048
6	7	274000000	1	0.00110	0.00034	0.00001	0.00035
6	8	5000000	1	0.00000	0.00048	0.00048	0.00096
6	9	5000000	0	0.00000	0.00048	0.00000	0.00048
7	4	1000000000	0	0.00160	0.00048	0.00000	0.00048
7	5	1000000000	0	0.00160	0.00048	0.00000	0.00048
7	6	274000000	1	0.00110	0.00034	0.00001	0.00035
7	10	5000000	1	0.00000	0.00048	0.00048	0.00096
7	11	5000000	0	0.00000	0.00048	0.00000	0.00048
8	6	5000000	1	0.00000	0.00048	0.00048	0.00096
8	9	5000000	1	0.00050	0.00063	0.00048	0.00111
8	12	2000000	0	0.00000	0.00120	0.00000	0.00120
8	13	2000000	1	0.00000	0.00120	0.00120	0.00240
9	6	5000000	0	0.00000	0.00048	0.00000	0.00048
9	8	5000000	1	0.00050	0.00063	0.00048	0.00111
9	10	5000000	1	0.00050	0.00063	0.00048	0.00111
9	13	2000000	0	0.00000	0.00120	0.00000	0.00120
9	14	2000000	1	0.00000	0.00120	0.00120	0.00240
10	7	5000000	1	0.00000	0.00048	0.00048	0.00096
10	9	5000000	1	0.00050	0.00063	0.00048	0.00111
10	11	5000000	1	0.00050	0.00063	0.00048	0.00111
10	14	2000000	0	0.00000	0.00120	0.00000	0.00120
10	15	2000000	1	0.00000	0.00120	0.00120	0.00240
11	7	5000000	0	0.00000	0.00048	0.00000	0.00048
11	10	5000000	1	0.00050	0.00063	0.00048	0.00111
11	15	2000000	0	0.00000	0.00120	0.00000	0.00120
11	16	2000000	1	0.00000	0.00120	0.00120	0.00240
12	8	2000000	0	0.00000	0.00120	0.00000	0.00120
13	8	2000000	1	0.00000	0.00120	0.00120	0.00240
13	9	2000000	0	0.00000	0.00120	0.00000	0.00120
14	9	2000000	1	0.00000	0.00120	0.00120	0.00240
14	10	2000000	0	0.00000	0.00120	0.00000	0.00120
15	10	2000000	1	0.00000	0.00120	0.00120	0.00240
15	11	2000000	0	0.00000	0.00120	0.00000	0.00120
16	11	2000000	1	0.00000	0.00120	0.00120	0.00240

Table 12. Calculation of Low-High Scenario Total Cost Per Packet

0.3 Delay Sensitivity
0.8 Detectibility
1000 Packet Size (bytes)

This table is used to calculate costs using the routes from Dijkstra's All-Pairs algorithm.
These costs are used to calculate better (lower cost) routes based on context.

From Node	To Node	Bandwidth (bps)	Detectible 0 = No 1 = Yes	Propagation + Queue Delay (sec)	Delay Sensitivity Cost	Detectibility Cost	Total Cost Per Packet
0	1	10000000000	0	0.12370	0.03711	0.00000	0.03711
1	0	10000000000	0	0.12370	0.03711	0.00000	0.03711
1	2	10000000000	0	0.00540	0.00162	0.00000	0.00162
1	3	10000000000	0	0.11830	0.03549	0.00000	0.03549
1	4	10000000000	0	0.11830	0.03549	0.00000	0.03549
2	1	10000000000	0	0.00540	0.00162	0.00000	0.00162
2	4	10000000000	0	0.11830	0.03549	0.00000	0.03549
2	5	10000000000	0	0.11830	0.03549	0.00000	0.03549
3	1	10000000000	0	0.11830	0.03549	0.00000	0.03549
3	4	10000000000	0	0.00160	0.00048	0.00000	0.00048
3	6	1000000000	0	0.00160	0.00048	0.00000	0.00048
4	1	10000000000	0	0.11830	0.03549	0.00000	0.03549
4	2	10000000000	0	0.11830	0.03549	0.00000	0.03549
4	3	10000000000	0	0.00160	0.00048	0.00000	0.00048
4	5	10000000000	0	0.00160	0.00048	0.00000	0.00048
4	6	1000000000	0	0.00160	0.00048	0.00000	0.00048
4	7	1000000000	0	0.00160	0.00048	0.00000	0.00048
5	2	10000000000	0	0.11830	0.03549	0.00000	0.03549
5	4	10000000000	0	0.00160	0.00048	0.00000	0.00048
5	7	1000000000	0	0.00160	0.00048	0.00000	0.00048
6	3	1000000000	0	0.00160	0.00048	0.00000	0.00048
6	4	1000000000	0	0.00160	0.00048	0.00000	0.00048
6	7	274000000	1	0.00110	0.00034	0.00002	0.00036
6	8	5000000	1	0.00000	0.00048	0.00128	0.00176
6	9	5000000	0	0.00000	0.00048	0.00000	0.00048
7	4	1000000000	0	0.00160	0.00048	0.00000	0.00048
7	5	1000000000	0	0.00160	0.00048	0.00000	0.00048
7	6	274000000	1	0.00110	0.00034	0.00002	0.00036
7	10	5000000	1	0.00000	0.00048	0.00128	0.00176
7	11	5000000	0	0.00000	0.00048	0.00000	0.00048
8	6	5000000	1	0.00000	0.00048	0.00128	0.00176
8	9	5000000	1	0.00050	0.00063	0.00128	0.00191
8	12	2000000	0	0.00000	0.00120	0.00000	0.00120
8	13	2000000	1	0.00000	0.00120	0.00320	0.00440
9	6	5000000	0	0.00000	0.00048	0.00000	0.00048
9	8	5000000	1	0.00050	0.00063	0.00128	0.00191
9	10	5000000	1	0.00050	0.00063	0.00128	0.00191
9	13	2000000	0	0.00000	0.00120	0.00000	0.00120
9	14	2000000	1	0.00000	0.00120	0.00320	0.00440
10	7	5000000	1	0.00000	0.00048	0.00128	0.00176
10	9	5000000	1	0.00050	0.00063	0.00128	0.00191
10	11	5000000	1	0.00050	0.00063	0.00128	0.00191
10	14	2000000	0	0.00000	0.00120	0.00000	0.00120
10	15	2000000	1	0.00000	0.00120	0.00320	0.00440
11	7	5000000	0	0.00000	0.00048	0.00000	0.00048
11	10	5000000	1	0.00050	0.00063	0.00128	0.00191
11	15	2000000	0	0.00000	0.00120	0.00000	0.00120
11	16	2000000	1	0.00000	0.00120	0.00320	0.00440
12	8	2000000	0	0.00000	0.00120	0.00000	0.00120
13	8	2000000	1	0.00000	0.00120	0.00320	0.00440
13	9	2000000	0	0.00000	0.00120	0.00000	0.00120
14	9	2000000	1	0.00000	0.00120	0.00320	0.00440
14	10	2000000	0	0.00000	0.00120	0.00000	0.00120
15	10	2000000	1	0.00000	0.00120	0.00320	0.00440
15	11	2000000	0	0.00000	0.00120	0.00000	0.00120
16	11	2000000	1	0.00000	0.00120	0.00320	0.00440

Table 13. Calculation of High-Low Scenario Total Cost Per Packet

0.8 Delay Sensitivity
0.3 Detectibility
1000 Packet Size (bytes)

This table is used to calculate costs using the routes from Dijkstra's All-Pairs algorithm.
These costs are used to calculate better (lower cost) routes based on context.

From Node	To Node	Bandwidth (bps)	Detectible 0 = No 1 = Yes	Propagation + Queue Delay (sec)	Delay Sensitivity Cost	Detectibility Cost	Total Cost Per Packet
0	1	10000000000	0	0.12370	0.09896	0.00000	0.09896
1	0	10000000000	0	0.12370	0.09896	0.00000	0.09896
1	2	10000000000	0	0.00540	0.00432	0.00000	0.00432
1	3	10000000000	0	0.11830	0.09464	0.00000	0.09464
1	4	10000000000	0	0.11830	0.09464	0.00000	0.09464
2	1	10000000000	0	0.00540	0.00432	0.00000	0.00432
2	4	10000000000	0	0.11830	0.09464	0.00000	0.09464
2	5	10000000000	0	0.11830	0.09464	0.00000	0.09464
3	1	10000000000	0	0.11830	0.09464	0.00000	0.09464
3	4	10000000000	0	0.00160	0.00128	0.00000	0.00128
3	6	1000000000	0	0.00160	0.00129	0.00000	0.00129
4	1	10000000000	0	0.11830	0.09464	0.00000	0.09464
4	2	10000000000	0	0.11830	0.09464	0.00000	0.09464
4	3	10000000000	0	0.00160	0.00128	0.00000	0.00128
4	5	10000000000	0	0.00160	0.00128	0.00000	0.00128
4	6	1000000000	0	0.00160	0.00129	0.00000	0.00129
4	7	1000000000	0	0.00160	0.00129	0.00000	0.00129
5	2	10000000000	0	0.11830	0.09464	0.00000	0.09464
5	4	10000000000	0	0.00160	0.00128	0.00000	0.00128
5	7	1000000000	0	0.00160	0.00129	0.00000	0.00129
6	3	1000000000	0	0.00160	0.00129	0.00000	0.00129
6	4	1000000000	0	0.00160	0.00129	0.00000	0.00129
6	7	274000000	1	0.00110	0.00090	0.00001	0.00091
6	8	5000000	1	0.00000	0.00128	0.00048	0.00176
6	9	5000000	0	0.00000	0.00128	0.00000	0.00128
7	4	1000000000	0	0.00160	0.00129	0.00000	0.00129
7	5	1000000000	0	0.00160	0.00129	0.00000	0.00129
7	6	274000000	1	0.00110	0.00090	0.00001	0.00091
7	10	5000000	1	0.00000	0.00128	0.00048	0.00176
7	11	5000000	0	0.00000	0.00128	0.00000	0.00128
8	6	5000000	1	0.00000	0.00128	0.00048	0.00176
8	9	5000000	1	0.00050	0.00168	0.00048	0.00216
8	12	2000000	0	0.00000	0.00320	0.00000	0.00320
8	13	2000000	1	0.00000	0.00320	0.00120	0.00440
9	6	5000000	0	0.00000	0.00128	0.00000	0.00128
9	8	5000000	1	0.00050	0.00168	0.00048	0.00216
9	10	5000000	1	0.00050	0.00168	0.00048	0.00216
9	13	2000000	0	0.00000	0.00320	0.00000	0.00320
9	14	2000000	1	0.00000	0.00320	0.00120	0.00440
10	7	5000000	1	0.00000	0.00128	0.00048	0.00176
10	9	5000000	1	0.00050	0.00168	0.00048	0.00216
10	11	5000000	1	0.00050	0.00168	0.00048	0.00216
10	14	2000000	0	0.00000	0.00320	0.00000	0.00320
10	15	2000000	1	0.00000	0.00320	0.00120	0.00440
11	7	5000000	0	0.00000	0.00128	0.00000	0.00128
11	10	5000000	1	0.00050	0.00168	0.00048	0.00216
11	15	2000000	0	0.00000	0.00320	0.00000	0.00320
11	16	2000000	1	0.00000	0.00320	0.00120	0.00440
12	8	2000000	0	0.00000	0.00320	0.00000	0.00320
13	8	2000000	1	0.00000	0.00320	0.00120	0.00440
13	9	2000000	0	0.00000	0.00320	0.00000	0.00320
14	9	2000000	1	0.00000	0.00320	0.00120	0.00440
14	10	2000000	0	0.00000	0.00320	0.00000	0.00320
15	10	2000000	1	0.00000	0.00320	0.00120	0.00440
15	11	2000000	0	0.00000	0.00320	0.00000	0.00320
16	11	2000000	1	0.00000	0.00320	0.00120	0.00440

Table 14. Calculation of High-High Scenario Total Cost Per Packet

0.8 Delay Sensitivity
0.8 Detectibility
1000 Packet Size (bytes)

This table is used to calculate costs using the routes from Dijkstra's All-Pairs algorithm.
These costs are used to calculate better (lower cost) routes based on context.

From Node	To Node	Bandwidth (bps)	Detectible 0 = No 1 = Yes	Propagation + Queue Delay (sec)	Delay Sensitivity Cost	Detectibility Cost	Total Cost Per Packet
0	1	10000000000	0	0.12370	0.09896	0.00000	0.09896
1	0	10000000000	0	0.12370	0.09896	0.00000	0.09896
1	2	10000000000	0	0.00540	0.00432	0.00000	0.00432
1	3	10000000000	0	0.11830	0.09464	0.00000	0.09464
1	4	10000000000	0	0.11830	0.09464	0.00000	0.09464
2	1	10000000000	0	0.00540	0.00432	0.00000	0.00432
2	4	10000000000	0	0.11830	0.09464	0.00000	0.09464
2	5	10000000000	0	0.11830	0.09464	0.00000	0.09464
3	1	10000000000	0	0.11830	0.09464	0.00000	0.09464
3	4	10000000000	0	0.00160	0.00128	0.00000	0.00128
3	6	1000000000	0	0.00160	0.00129	0.00000	0.00129
4	1	10000000000	0	0.11830	0.09464	0.00000	0.09464
4	2	10000000000	0	0.11830	0.09464	0.00000	0.09464
4	3	10000000000	0	0.00160	0.00128	0.00000	0.00128
4	5	10000000000	0	0.00160	0.00128	0.00000	0.00128
4	6	1000000000	0	0.00160	0.00129	0.00000	0.00129
4	7	1000000000	0	0.00160	0.00129	0.00000	0.00129
5	2	10000000000	0	0.11830	0.09464	0.00000	0.09464
5	4	10000000000	0	0.00160	0.00128	0.00000	0.00128
5	7	1000000000	0	0.00160	0.00129	0.00000	0.00129
6	3	1000000000	0	0.00160	0.00129	0.00000	0.00129
6	4	1000000000	0	0.00160	0.00129	0.00000	0.00129
6	7	274000000	1	0.00110	0.00090	0.00002	0.00093
6	8	5000000	1	0.00000	0.00128	0.00128	0.00256
6	9	5000000	0	0.00000	0.00128	0.00000	0.00128
7	4	1000000000	0	0.00160	0.00129	0.00000	0.00129
7	5	1000000000	0	0.00160	0.00129	0.00000	0.00129
7	6	274000000	1	0.00110	0.00090	0.00002	0.00093
7	10	5000000	1	0.00000	0.00128	0.00128	0.00256
7	11	5000000	0	0.00000	0.00128	0.00000	0.00128
8	6	5000000	1	0.00000	0.00128	0.00128	0.00256
8	9	5000000	1	0.00050	0.00168	0.00128	0.00296
8	12	2000000	0	0.00000	0.00320	0.00000	0.00320
8	13	2000000	1	0.00000	0.00320	0.00320	0.00640
9	6	5000000	0	0.00000	0.00128	0.00000	0.00128
9	8	5000000	1	0.00050	0.00168	0.00128	0.00296
9	10	5000000	1	0.00050	0.00168	0.00128	0.00296
9	13	2000000	0	0.00000	0.00320	0.00000	0.00320
9	14	2000000	1	0.00000	0.00320	0.00320	0.00640
10	7	5000000	1	0.00000	0.00128	0.00128	0.00256
10	9	5000000	1	0.00050	0.00168	0.00128	0.00296
10	11	5000000	1	0.00050	0.00168	0.00128	0.00296
10	14	2000000	0	0.00000	0.00320	0.00000	0.00320
10	15	2000000	1	0.00000	0.00320	0.00320	0.00640
11	7	5000000	0	0.00000	0.00128	0.00000	0.00128
11	10	5000000	1	0.00050	0.00168	0.00128	0.00296
11	15	2000000	0	0.00000	0.00320	0.00000	0.00320
11	16	2000000	1	0.00000	0.00320	0.00320	0.00640
12	8	2000000	0	0.00000	0.00320	0.00000	0.00320
13	8	2000000	1	0.00000	0.00320	0.00320	0.00640
13	9	2000000	0	0.00000	0.00320	0.00000	0.00320
14	9	2000000	1	0.00000	0.00320	0.00320	0.00640
14	10	2000000	0	0.00000	0.00320	0.00000	0.00320
15	10	2000000	1	0.00000	0.00320	0.00320	0.00640
15	11	2000000	0	0.00000	0.00320	0.00000	0.00320
16	11	2000000	1	0.00000	0.00320	0.00320	0.00640

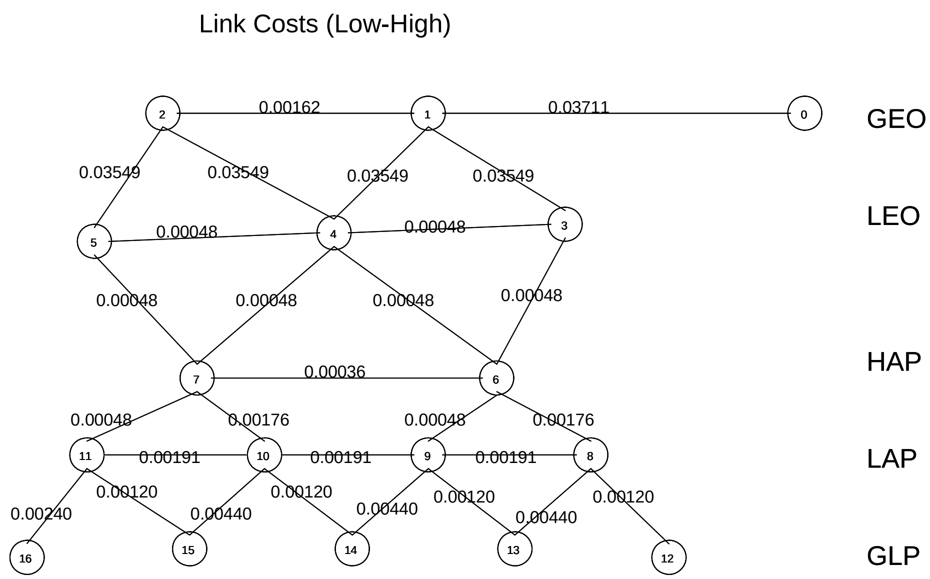

Figure 10. Low-High Scenario Link Costs

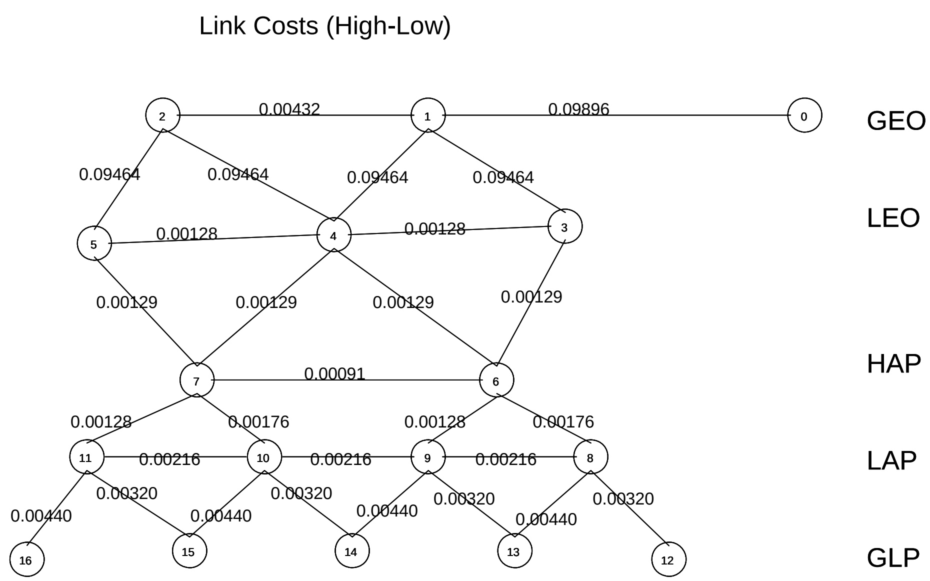

Figure 11. High-Low Scenario Link Costs

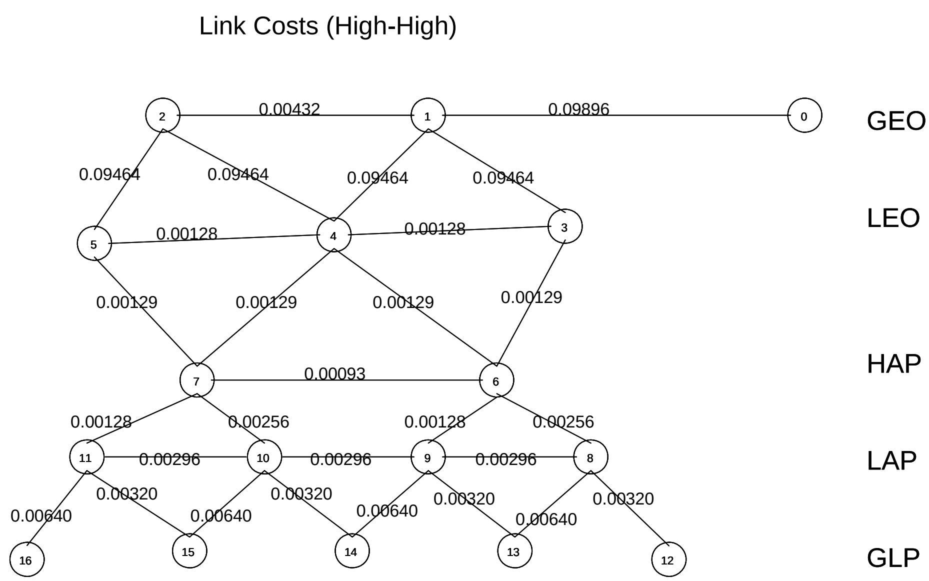

Figure 12. High-High Scenario Link Costs

Context-based Routing (Low-High)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	--	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	0	--	2	3	4	2	3	4	3	3	4	4	3	3	4	4	4
2	1	1	--	1	4	5	4	4	4	4	4	4	4	4	4	4	4
3	1	1	1	--	4	4	6	4	6	6	4	4	6	6	6	4	4
4	1	1	2	3	--	5	6	7	6	6	7	7	6	6	7	7	7
5	2	2	2	4	4	--	4	7	4	4	7	7	4	4	7	7	7
6	3	3	4	3	4	4	--	7	8	9	7	7	8	9	9	7	7
7	4	4	4	4	4	5	6	--	6	6	10	11	6	6	10	11	11
8	6	6	6	6	6	6	6	6	--	9	9	6	12	9	9	9	6
9	6	6	6	6	6	6	6	6	8	--	10	10	8	13	14	10	10
10	7	7	7	7	7	7	7	7	9	9	--	11	9	9	14	11	11
11	7	7	7	7	7	7	7	7	7	10	10	--	7	10	10	15	16
12	8	8	8	8	8	8	8	8	8	8	8	8	--	8	8	8	8
13	9	8	8	8	8	8	8	8	9	9	9	9	8	--	9	9	9
14	9	9	9	9	9	10	9	10	9	9	10	10	9	9	--	10	10
15	11	10	10	10	10	10	10	10	10	10	10	11	10	10	10	--	11
16	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	--

Figure 13. Low-High Scenario Context-Based Routing Table

Context-based Routing (High-Low)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	--	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	0	--	2	3	4	2	3	4	3	3	4	4	3	3	4	4	4
2	1	1	--	1	4	5	4	4	4	4	4	4	4	4	4	4	4
3	1	1	1	--	4	4	6	4	6	6	4	4	6	6	6	4	4
4	1	1	2	3	--	5	6	7	6	6	7	7	6	6	7	7	7
5	2	2	2	4	4	--	4	7	4	4	7	7	4	4	7	7	7
6	3	3	4	3	4	4	--	7	8	9	7	7	8	9	9	7	7
7	4	4	4	4	4	5	6	--	6	6	10	11	6	6	10	11	11
8	6	6	6	6	6	6	6	6	--	9	9	6	12	13	9	9	6
9	6	6	6	6	6	6	6	6	8	--	10	10	8	13	14	10	10
10	7	7	7	7	7	7	7	7	9	9	--	11	9	9	14	15	11
11	7	7	7	7	7	7	7	7	7	10	10	--	7	10	10	15	16
12	8	8	8	8	8	8	8	8	8	8	8	8	--	8	8	8	8
13	9	8	8	8	8	8	8	8	8	9	9	9	8	--	9	9	9
14	9	9	9	9	9	10	9	10	9	9	10	10	9	9	--	10	10
15	11	10	10	10	10	10	10	10	10	10	10	11	10	10	10	--	11
16	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	--

Figure 14. High-Low Scenario Context-Based Routing Table

Context-based Routing (High-High)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	--	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	0	--	2	3	4	2	3	4	3	3	4	4	3	3	4	4	4
2	1	1	--	1	4	5	4	4	4	4	4	4	4	4	4	4	4
3	1	1	1	--	4	4	6	4	6	6	4	4	6	6	6	4	4
4	1	1	2	3	--	5	6	7	6	6	7	7	6	6	7	7	7
5	2	2	2	4	4	--	4	7	4	4	7	7	4	4	7	7	7
6	3	3	4	3	4	4	--	7	8	9	7	7	8	9	9	7	7
7	4	4	4	4	4	5	6	--	6	6	10	11	6	6	11	11	11
8	6	6	6	6	6	6	6	6	--	9	9	6	12	9	9	9	6
9	6	6	6	6	6	6	6	6	8	--	10	10	8	13	14	10	10
10	7	7	7	7	7	7	7	7	9	9	--	11	9	9	14	11	11
11	7	7	7	7	7	7	7	7	7	10	10	--	7	10	10	15	16
12	8	8	8	8	8	8	8	8	8	8	8	8	--	8	8	8	8
13	9	8	8	8	8	8	8	8	9	9	9	9	8	--	9	9	9
14	9	9	9	9	9	10	9	10	9	9	10	10	9	9	--	10	10
15	11	10	10	10	10	10	10	10	10	10	10	11	10	10	10	--	11
16	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	--

Figure 15. High-High Scenario Context-Based Routing Table

Table 15. Calculation of Baseline Scenario Bandwidth

Time (sec)	bwl0.tr	bwl1.tr	bwl2.tr	bwl3.tr	bwl4.tr	bwl5.tr	bwl6.tr	bwl7.tr	bwl8.tr	Dijkstra Bandwidth (Mbits/sec)
0	0	0	0	0	0	0	0	0	0	0
0.25	0	0	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0
0.75	0	1.376	0.576	0.256	0.352	0	0	0	1.184	3.744
1	0.832	2.016	0.288	0.992	0.96	0	0.704	0	1.792	7.584
1.25	2.368	1.664	0.832	0.992	0	0.8	1.344	0	2.016	10.016
1.5	2.816	0.128	0.992	0.832	0.384	1.024	1.824	0	1.984	9.984
1.75	3.168	0.48	0.992	0.992	0.992	0.992	2.56	0	1.536	11.712
2	3.328	1.504	1.024	0.992	0.8	0.992	3.008	0	2.016	13.664
2.25	3.968	1.856	0.992	0.992	0.352	0.992	3.008	0	1.6	13.76
2.5	3.488	1.216	0.992	0.736	0.096	1.024	1.952	0	0.032	9.536
2.75	3.552	0.992	0.992	0.992	0	0.992	1.472	0.224	1.024	10.24
3	2.688	1.888	1.024	0.512	0.192	0.992	2.176	0.992	2.016	12.48
3.25	2.88	1.984	0.992	0	0.32	0.992	2.016	0.992	1.984	12.16
3.5	2.912	0.992	0.224	0.768	0.992	1.024	1.984	0.992	2.016	11.904
3.75	3.232	0.672	0	0.992	0.384	0.992	2.016	1.024	1.984	11.296
4	2.4	0.992	0.352	0.992	0.416	0.992	1.984	0.992	2.016	11.136
4.25	3.904	1.664	0.992	0.992	1.024	0.992	2.848	0.992	1.984	15.392
4.5	3.392	1.536	0.992	1.024	0.224	1.024	2.368	0.992	2.016	13.568
4.75	3.584	0.992	1.024	0.992	0.32	0.992	2.464	1.024	1.984	13.376
5	3.712	0.576	0.96	0.992	0.512	0.992	2.336	0.288	2.016	12.384
5.25	3.52	0.992	1.024	0.864	0.992	0.896	1.984	0	1.44	11.712
5.5	2.72	1.056	0.512	0.096	0.896	1.024	2.112	0	1.984	10.4
5.75	3.264	0.992	0.992	0.992	1.024	0.992	2.912	0	2.016	13.184
6	2.816	0.64	0.992	0.992	0.448	0.992	2.752	0	1.632	11.264
6.25	3.584	0	1.024	0.992	0.8	0.992	1.984	0	0.992	10.368
6.5	2.944	0.704	0.992	0.832	0.096	1.024	1.216	0	1.472	9.28
6.75	2.976	1.024	0.992	0.992	0.96	0.032	0.992	0	1.984	9.952
7	3.008	0.832	0.992	0.864	0.384	0	1.152	0.512	1.696	9.44
7.25	2.624	0.576	1.024	1.024	0.192	0	1.984	0.992	2.016	10.432
7.5	2.176	1.536	0.448	0.992	0.992	0	1.984	1.024	1.984	11.136
7.75	3.648	1.312	0.544	0.64	1.024	0	1.024	0.992	2.016	11.2
8	2.784	0.992	1.024	0.736	0.544	0.16	0.288	0.992	1.984	9.504
8.25	3.36	0.288	0.992	0.768	0.992	1.024	1.344	0.992	2.016	11.776
8.5	4	0.288	0.992	0.288	0.992	0.992	2.08	0.96	1.984	12.576
8.75	2.976	1.76	0.992	0	1.024	0.992	2.72	0.992	2.016	13.472
9	3.584	2.016	0.896	0.768	0.992	0.896	2.432	1.024	1.984	14.592
9.25	2.656	1.088	0.352	0.768	0.992	0.704	2.016	0.992	2.016	11.584
9.5	2.848	1.696	0	0	0.992	0.512	3.008	0.064	1.984	11.104
9.75	3.84	1.856	0	0.448	0.704	0	3.008	0	2.016	11.872
10	3.84	0.992	0	0.992	0.544	0.096	2.752	0.736	1.984	11.936
10.25	3.104	1.408	0.16	0.992	0.96	0	1.92	0	2.016	10.56
10.5	2.752	1.44	0.992	0.896	0.992	0.288	0.448	0	1.984	9.792
10.75	2.112	0.48	0.992	0.608	1.024	1.024	0.032	0	0.832	7.104
11	2.272	0	0.864	0.992	0.992	0.992	0.352	0.288	0.96	7.712
11.25	2.976	0.192	0.992	1.024	0.992	0.128	0.192	0.992	0.992	8.48
11.5	3.36	0.256	0.192	0.992	0.992	0.032	0.896	0.448	0.992	8.16
11.75	3.552	1.056	0.672	0.992	1.024	0.928	1.312	0.384	1.792	11.712
12	3.264	0.064	0.512	1.024	0.992	0.992	1.568	0.64	1.984	11.04
12.25	3.104	0.896	0	0.992	0.992	0.8	1.984	0.704	0.192	9.664
12.5	2.848	0.256	0.128	0.96	0.928	1.024	2.72	0.896	0.928	10.688
12.75	2.752	0.832	0.96	0.448	0.736	0.128	2.496	0.448	1.728	10.528
13	2.496	1.024	0.032	1.024	0.992	0	1.984	0.992	1.728	10.272
13.25	2.784	1.12	0.992	0.992	1.024	0	2.528	0.544	1.856	11.84
13.5	2.08	2.016	0.992	0.896	0.992	0	1.216	0	1.408	9.6
13.75	3.104	1.888	0.608	0.608	0.768	0	1.184	0	1.152	9.312
14	3.872	1.6	0.992	0.416	0.992	0	2.176	0	1.344	11.392
14.25	3.584	1.344	1.024	0.8	0.992	0	2.304	0	2.016	12.064
14.5	3.232	1.952	0.48	0.992	1.024	0	1.984	0	0.608	10.272
14.75	2.816	0.032	0	0.032	0	0	0.032	0	0.384	3.296

Table 16. Calculation of Low-Low Scenario Bandwidth

Time (sec)	bwl0.tr	bwl1.tr	bwl2.tr	bwl3.tr	bwl4.tr	bwl5.tr	bwl6.tr	bwl7.tr	bwl8.tr	Low-Low Bandwidth (Mbits/sec)
0	0	0	0	0	0	0	0	0	0	0
0.25	0	0	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0
0.75	0	1.376	0.576	0.16	0.288	0	0	0	1.184	3.584
1	0.768	2.016	0.288	0.672	0.672	0	0.704	0	1.792	6.912
1.25	2.048	1.664	0.832	0.832	0.352	0.8	1.344	0	1.984	9.856
1.5	2.624	0.128	0.992	0.992	0	1.024	1.728	0	2.016	9.504
1.75	3.2	0.48	0.992	0.608	0.576	0.992	1.984	0	1.536	10.368
2	3.392	1.504	1.024	1.024	0.928	0.992	2.016	0	2.016	12.896
2.25	3.008	1.856	0.992	0.992	0.576	0.992	1.984	0	1.6	12
2.5	2.944	1.216	0.992	0.832	0.448	1.024	2.016	0	0.032	9.504
2.75	3.264	0.992	0.992	0.992	0	0.992	1.984	0.192	1.024	10.432
3	2.688	1.888	1.024	1.024	0	0.992	2.016	1.024	2.016	12.672
3.25	3.2	1.984	0.992	0.16	0.48	0.992	1.984	0.992	1.984	12.768
3.5	3.232	0.992	0.224	0.704	0.96	1.024	2.016	0.992	2.016	12.16
3.75	3.232	0.672	0	1.056	0.448	0.992	1.984	0.992	1.984	11.36
4	2.4	0.992	0.352	0.832	0.288	0.992	2.016	1.024	2.016	10.912
4.25	3.776	1.664	0.992	0.672	0.672	0.992	1.984	0.992	1.984	13.728
4.5	3.52	1.536	0.992	0.896	0.704	1.024	2.016	0.992	2.016	13.696
4.75	3.36	0.992	1.024	1.344	0.032	0.992	1.984	0.992	1.984	12.704
5	3.648	0.576	0.96	0.64	0.672	0.992	2.016	0.32	2.016	11.84
5.25	3.2	0.992	1.024	0.832	0.352	0.896	1.984	0	1.44	10.72
5.5	2.56	1.056	0.512	0.64	0.352	1.024	2.016	0	1.984	10.144
5.75	3.36	0.992	0.992	0.352	0.928	0.992	1.984	0	2.016	11.616
6	2.72	0.64	0.992	0.064	0.992	0.992	2.016	0	1.632	10.048
6.25	3.584	0	1.024	0.736	0.256	0.992	1.984	0	0.992	9.568
6.5	3.136	0.704	0.992	0.288	0.864	1.024	2.016	0	1.472	10.496
6.75	2.816	1.024	0.992	0.864	0.224	0.032	1.728	0	1.984	9.664
7	3.232	0.832	0.992	0.96	0.416	0	1.152	0.512	1.696	9.792
7.25	2.848	0.576	1.024	1.216	0.16	0	1.984	0.992	1.984	10.784
7.5	2.016	1.536	0.448	0.736	0.512	0	1.984	0.992	2.016	10.24
7.75	3.456	1.312	0.544	0.928	0.224	0	1.024	1.024	1.984	10.496
8	2.944	0.992	1.024	0.512	0.704	0.16	0.288	0.992	2.016	9.632
8.25	3.2	0.288	0.992	0.864	0.416	1.024	1.312	0.992	1.984	11.072
8.5	3.744	0.288	0.992	0.768	0.992	0.992	1.888	0.96	2.016	12.64
8.75	2.368	1.76	0.992	0.064	1.28	0.992	1.984	0.992	1.984	12.416
9	3.616	2.016	0.896	0.224	0.992	0.896	2.016	0.992	2.016	13.664
9.25	2.656	1.088	0.352	0.672	0.736	0.704	1.984	1.024	1.984	11.2
9.5	2.784	1.696	0	0.224	0.992	0.512	2.016	0.064	2.016	10.304
9.75	3.648	1.856	0	0	0.928	0	1.984	0	1.984	10.4
10	3.904	0.992	0	0.64	0.768	0.096	2.016	0.736	2.016	11.168
10.25	3.296	1.408	0.16	1.056	0.512	0	1.984	0	1.984	10.4
10.5	2.208	1.44	0.992	0.96	0.992	0.288	1.728	0	2.016	10.624
10.75	1.632	0.48	0.992	0.96	1.056	1.024	0.032	0	0.8	6.976
11	1.568	0	0.864	0.224	0.864	0.992	0.352	0.288	0.992	6.144
11.25	2.944	0.192	0.992	0.096	0.992	0.128	0.192	0.992	0.992	7.52
11.5	3.744	0.256	0.192	0.448	0.992	0.032	0.896	0.448	0.992	8
11.75	3.136	1.056	0.672	0	0.992	0.928	1.28	0.384	1.792	10.24
12	3.232	0.064	0.512	0	1.024	0.992	1.568	0.64	1.984	10.016
12.25	3.264	0.896	0	0.288	0.992	0.8	1.984	0.672	0.192	9.088
12.5	2.72	0.256	0.128	0.16	0.832	1.024	2.016	0.928	0.896	8.96
12.75	2.784	0.832	0.96	0.736	0.256	0.128	1.984	0.448	1.76	9.888
13	2.56	1.024	0.032	0.672	0.736	0	2.016	0.992	1.728	9.76
13.25	2.368	1.12	0.992	0.992	0.992	0	1.984	0.544	1.856	10.848
13.5	1.28	2.016	0.992	0.992	0	0	2.016	0	1.376	8.672
13.75	3.136	1.888	0.608	0.704	0.32	0	1.952	0	1.184	9.792
14	3.872	1.6	0.992	0.256	0.736	0	1.664	0	1.344	10.464
14.25	3.552	1.344	1.024	0.384	0.608	0	1.984	0	1.984	10.88
14.5	3.232	1.952	0.48	0	1.024	0	2.016	0	0.64	9.344
14.75	2.848	0.032	0	0	0.768	0	0.832	0	0.384	4.864

Table 17. Calculation of Low-High Scenario Bandwidth

Time (sec)	bwl0.tr	bwl1.tr	bwl2.tr	bwl3.tr	bwl4.tr	bwl5.tr	bwl6.tr	bwl7.tr	bwl8.tr	Low-High Bandwidth (Mbits/sec)
0	0	0	0	0	0	0	0	0	0	0
0.25	0	0	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0
0.75	0	1.376	0.576	0.16	0.288	0	0	0	1.184	3.584
1	0.768	2.016	0.288	0.672	0.672	0	0.704	0	1.792	6.912
1.25	2.048	1.664	0.832	0.832	0.352	0.8	1.344	0	1.984	9.856
1.5	2.624	0.128	0.992	0.992	0	1.024	1.728	0	2.016	9.504
1.75	3.2	0.48	0.992	0.608	0.576	0.992	1.984	0	1.536	10.368
2	3.392	1.504	1.024	1.024	0.928	0.992	2.016	0	2.016	12.896
2.25	3.008	1.856	0.992	0.992	0.576	0.992	1.984	0	1.6	12
2.5	2.944	1.216	0.992	0.832	0.448	1.024	2.016	0	0.032	9.504
2.75	3.264	0.992	0.992	0.992	0	0.992	1.984	0.224	1.024	10.464
3	2.688	1.888	1.024	1.024	0	0.992	2.016	0.992	2.016	12.64
3.25	3.2	1.984	0.992	0.16	0.48	0.992	1.984	0.992	1.984	12.768
3.5	3.232	0.992	0.224	0.704	0.96	1.024	2.016	0.992	2.016	12.16
3.75	3.232	0.672	0	1.056	0.448	0.992	1.984	1.024	1.984	11.392
4	2.4	0.992	0.352	0.832	0.288	0.992	2.016	0.992	2.016	10.88
4.25	3.776	1.664	0.992	0.672	0.672	0.992	1.984	0.992	1.984	13.728
4.5	3.52	1.536	0.992	0.896	0.704	1.024	2.016	0.992	2.016	13.696
4.75	3.36	0.992	1.024	1.344	0.032	0.992	1.984	1.024	1.984	12.736
5	3.648	0.576	0.96	0.64	0.672	0.992	2.016	0.288	2.016	11.808
5.25	3.2	0.992	1.024	0.832	0.352	0.896	1.984	0	1.44	10.72
5.5	2.56	1.056	0.512	0.64	0.352	1.024	2.016	0	1.984	10.144
5.75	3.36	0.992	0.992	0.352	0.928	0.992	1.984	0	2.016	11.616
6	2.72	0.64	0.992	0.064	0.992	0.992	2.016	0	1.632	10.048
6.25	3.584	0	1.024	0.736	0.256	0.992	1.984	0	0.992	9.568
6.5	3.136	0.704	0.992	0.288	0.864	1.024	2.016	0	1.472	10.496
6.75	2.816	1.024	0.992	0.864	0.224	0.032	1.728	0	1.984	9.664
7	3.232	0.832	0.992	0.96	0.416	0	1.152	0.512	1.696	9.792
7.25	2.848	0.576	1.024	1.216	0.16	0	1.984	0.992	1.984	10.784
7.5	2.016	1.536	0.448	0.736	0.512	0	1.984	1.024	2.016	10.272
7.75	3.456	1.312	0.544	0.928	0.224	0	1.024	0.992	1.984	10.464
8	2.944	0.992	1.024	0.512	0.704	0.16	0.288	0.992	2.016	9.632
8.25	3.2	0.288	0.992	0.864	0.416	1.024	1.312	0.992	1.984	11.072
8.5	3.744	0.288	0.992	0.768	0.992	0.992	1.888	0.96	2.016	12.64
8.75	2.368	1.76	0.992	0.064	1.28	0.992	1.984	0.992	1.984	12.416
9	3.616	2.016	0.896	0.224	0.992	0.896	2.016	1.024	2.016	13.696
9.25	2.656	1.088	0.352	0.672	0.736	0.704	1.984	0.992	1.984	11.168
9.5	2.784	1.696	0	0.224	0.992	0.512	2.016	0.064	2.016	10.304
9.75	3.648	1.856	0	0	0.928	0	1.984	0	1.984	10.4
10	3.904	0.992	0	0.64	0.768	0.096	2.016	0.736	2.016	11.168
10.25	3.296	1.408	0.16	1.056	0.512	0	1.984	0	1.984	10.4
10.5	2.208	1.44	0.992	0.96	0.992	0.288	1.728	0	2.016	10.624
10.75	1.632	0.48	0.992	0.96	1.056	1.024	0.032	0	0.8	6.976
11	1.568	0	0.864	0.224	0.864	0.992	0.352	0.288	0.992	6.144
11.25	2.944	0.192	0.992	0.096	0.992	0.128	0.192	0.992	0.992	7.52
11.5	3.744	0.256	0.192	0.448	0.992	0.032	0.896	0.448	0.992	8
11.75	3.136	1.056	0.672	0	0.992	0.928	1.28	0.384	1.792	10.24
12	3.232	0.064	0.512	0	1.024	0.992	1.568	0.64	1.984	10.016
12.25	3.264	0.896	0	0.288	0.992	0.8	1.984	0.704	0.192	9.12
12.5	2.72	0.256	0.128	0.16	0.832	1.024	2.016	0.896	0.896	8.928
12.75	2.784	0.832	0.96	0.736	0.256	0.128	1.984	0.448	1.76	9.888
13	2.56	1.024	0.032	0.672	0.736	0	2.016	0.992	1.728	9.76
13.25	2.368	1.12	0.992	0.992	0.992	0	1.984	0.544	1.856	10.848
13.5	1.28	2.016	0.992	0.992	0	0	2.016	0	1.376	8.672
13.75	3.136	1.888	0.608	0.704	0.32	0	1.952	0	1.184	9.792
14	3.872	1.6	0.992	0.256	0.736	0	1.664	0	1.344	10.464
14.25	3.552	1.344	1.024	0.384	0.608	0	1.984	0	1.984	10.88
14.5	3.232	1.952	0.48	0	1.024	0	2.016	0	0.64	9.344
14.75	2.848	0.032	0	0	0.768	0	0.832	0	0.384	4.864

Table 18. Calculation of High-Low Scenario Bandwidth

Time (sec)	bwl0.tr	bwl1.tr	bwl2.tr	bwl3.tr	bwl4.tr	bwl5.tr	bwl6.tr	bwl7.tr	bwl8.tr	High-Low Bandwidth (Mbits/sec)
0	0	0	0	0	0	0	0	0	0	0
0.25	0	0	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0
0.75	0	1.376	0.576	0.256	0.352	0	0	0	1.184	3.744
1	0.832	2.016	0.288	0.992	0.96	0	0.704	0	2.176	7.968
1.25	2.368	1.664	0.832	0.992	0	0.8	1.344	0	2.848	10.848
1.5	2.848	0.128	0.992	0.832	0.384	1.024	1.824	0	1.28	9.312
1.75	3.168	0.48	0.992	0.992	0.992	0.992	2.56	0	1.056	11.232
2	3.296	1.504	1.024	0.992	0.8	0.992	2.976	0	2.336	13.92
2.25	4	1.856	0.992	0.992	0.352	0.992	3.04	0	1.248	13.472
2.5	3.488	1.216	0.992	0.736	0.096	1.024	1.952	0	0.032	9.536
2.75	3.52	0.992	0.992	0.992	0	0.992	1.472	0.224	1.056	10.24
3	2.688	1.888	1.024	0.512	0.192	0.992	2.176	0.992	1.984	12.448
3.25	2.88	1.984	0.992	0	0.288	0.992	2.016	0.992	1.984	12.128
3.5	2.912	0.992	0.224	0.768	1.024	1.024	1.984	0.992	2.016	11.936
3.75	3.232	0.672	0	1.024	0.384	0.992	2.016	1.024	2.336	11.68
4	2.4	0.992	0.352	0.96	0.416	0.992	1.984	0.992	3.008	12.096
4.25	3.936	1.664	0.992	0.992	1.024	0.992	2.848	0.992	1.952	15.392
4.5	3.36	1.536	0.992	1.024	0.224	1.024	2.368	0.992	2.592	14.112
4.75	3.584	0.992	1.024	0.992	0.32	0.992	2.464	1.024	2.144	13.536
5	3.712	0.576	0.96	0.992	0.512	0.992	2.336	0.288	0.992	11.36
5.25	3.52	0.992	1.024	0.864	0.96	0.896	1.984	0	1.024	11.264
5.5	2.752	1.056	0.512	0.096	0.928	1.024	2.112	0	1.984	10.464
5.75	3.232	0.992	0.992	0.992	1.024	0.992	2.912	0	2.048	13.184
6	2.816	0.64	0.992	0.992	0.448	0.992	2.752	0	1.6	11.232
6.25	3.584	0	1.024	1.024	0.768	0.992	2.016	0	0.992	10.4
6.5	2.976	0.704	0.992	0.8	0.128	1.024	1.184	0	1.472	9.28
6.75	2.976	1.024	0.992	0.992	0.96	0.032	0.992	0	2.016	9.984
7	2.976	0.832	0.992	0.864	0.384	0	1.152	0.512	1.664	9.376
7.25	2.624	0.576	1.024	1.024	0.192	0	1.984	0.992	2.016	10.432
7.5	2.176	1.536	0.448	0.992	0.992	0	1.984	1.024	2.944	12.096
7.75	3.648	1.312	0.544	0.64	1.024	0	1.024	0.992	2.592	11.776
8	2.784	0.992	1.024	0.736	0.544	0.16	0.288	0.992	1.28	8.8
8.25	3.36	0.288	0.992	0.768	0.992	1.024	1.344	0.992	1.408	11.168
8.5	4	0.288	0.992	0.288	0.992	0.992	2.08	0.96	2.4	12.992
8.75	2.976	1.76	0.992	0	1.024	0.992	2.72	0.992	2.336	13.792
9	3.584	2.016	0.896	0.768	0.992	0.896	2.432	1.024	3.008	15.616
9.25	2.656	1.088	0.352	0.768	0.992	0.704	2.016	0.992	2.848	12.416
9.5	2.848	1.696	0	0	0.992	0.512	3.008	0.064	2.816	11.936
9.75	3.84	1.856	0	0.448	0.704	0	3.008	0	2.72	12.576
10	3.808	0.992	0	0.992	0.544	0.096	2.752	0.736	1.984	11.904
10.25	3.136	1.408	0.16	0.992	0.96	0	1.92	0	1.92	10.496
10.5	2.752	1.44	0.992	0.896	0.992	0.288	0.448	0	0.64	8.448
10.75	2.112	0.48	0.992	0.608	0.992	1.024	0.032	0	0.736	6.976
11	2.272	0	0.864	1.024	0.992	0.992	0.352	0.288	0.96	7.744
11.25	3.008	0.192	0.992	0.992	1.024	0.128	0.192	0.992	0.992	8.512
11.5	3.328	0.256	0.192	0.992	0.992	0.032	0.896	0.448	0.992	8.128
11.75	3.552	1.056	0.672	0.992	1.024	0.928	1.312	0.384	1.792	11.712
12	3.264	0.064	0.512	1.024	0.992	0.992	1.568	0.64	2.112	11.168
12.25	3.104	0.896	0	0.992	0.992	0.8	1.984	0.704	0.064	9.536
12.5	2.848	0.256	0.128	0.96	0.928	1.024	2.72	0.896	0.928	10.688
12.75	2.752	0.832	0.96	0.448	0.736	0.128	2.496	0.448	1.76	10.56
13	2.496	1.024	0.032	1.024	0.992	0	2.016	0.992	1.696	10.272
13.25	2.784	1.12	0.992	0.992	1.024	0	2.496	0.544	1.856	11.808
13.5	2.08	2.016	0.992	0.896	0.992	0	1.216	0	1.408	9.6
13.75	3.104	1.888	0.608	0.608	0.768	0	1.184	0	1.152	9.312
14	3.872	1.6	0.992	0.416	0.992	0	2.144	0	1.344	11.36
14.25	3.552	1.344	1.024	0.8	0.992	0	2.336	0	2.016	12.064
14.5	3.264	1.952	0.48	0.992	1.024	0	1.984	0	0.608	10.304
14.75	2.816	0.032	0	0.032	0	0	0.032	0	0.384	3.296

Table 19. Calculation of High-High Scenario Bandwidth

Time (sec)	bwl0.tr	bwl1.tr	bwl2.tr	bwl3.tr	bwl4.tr	bwl5.tr	bwl6.tr	bwl7.tr	bwl8.tr	High-High Bandwidth (Mbits/sec)
0	0	0	0	0	0	0	0	0	0	0
0.25	0	0	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0
0.75	0	1.376	0.576	0.16	0.288	0	0	0	1.184	3.584
1	0.768	2.016	0.288	0.672	0.672	0	0.704	0	1.792	6.912
1.25	2.048	1.664	0.832	0.832	0.352	0.8	1.344	0	1.984	9.856
1.5	2.624	0.128	0.992	0.992	0	1.024	1.728	0	2.016	9.504
1.75	3.2	0.48	0.992	0.608	0.576	0.992	1.984	0	1.536	10.368
2	3.392	1.504	1.024	1.024	0.928	0.992	2.016	0	2.016	12.896
2.25	3.008	1.856	0.992	0.992	0.576	0.992	1.984	0	1.6	12
2.5	2.944	1.216	0.992	0.832	0.448	1.024	2.016	0	0.032	9.504
2.75	3.264	0.992	0.992	0.992	0	0.992	1.984	0.192	1.024	10.432
3	2.688	1.888	1.024	1.024	0	0.992	2.016	1.024	2.016	12.672
3.25	3.2	1.984	0.992	0.16	0.48	0.992	1.984	0.992	1.984	12.768
3.5	3.232	0.992	0.224	0.704	0.96	1.024	2.016	0.992	2.016	12.16
3.75	3.232	0.672	0	1.056	0.448	0.992	1.984	0.992	1.984	11.36
4	2.4	0.992	0.352	0.832	0.288	0.992	2.016	1.024	2.016	10.912
4.25	3.776	1.664	0.992	0.672	0.672	0.992	1.984	0.992	1.984	13.728
4.5	3.52	1.536	0.992	0.896	0.704	1.024	2.016	0.992	2.016	13.696
4.75	3.36	0.992	1.024	1.344	0.032	0.992	1.984	0.992	1.984	12.704
5	3.648	0.576	0.96	0.64	0.672	0.992	2.016	0.32	2.016	11.84
5.25	3.2	0.992	1.024	0.832	0.352	0.896	1.984	0	1.44	10.72
5.5	2.56	1.056	0.512	0.64	0.352	1.024	2.016	0	1.984	10.144
5.75	3.36	0.992	0.992	0.352	0.928	0.992	1.984	0	2.016	11.616
6	2.72	0.64	0.992	0.064	0.992	0.992	2.016	0	1.632	10.048
6.25	3.584	0	1.024	0.736	0.256	0.992	1.984	0	0.992	9.568
6.5	3.136	0.704	0.992	0.288	0.864	1.024	2.016	0	1.472	10.496
6.75	2.816	1.024	0.992	0.864	0.224	0.032	1.728	0	1.984	9.664
7	3.232	0.832	0.992	0.96	0.416	0	1.152	0.512	1.696	9.792
7.25	2.848	0.576	1.024	1.216	0.16	0	1.984	0.992	1.984	10.784
7.5	2.016	1.536	0.448	0.736	0.512	0	1.984	0.992	2.016	10.24
7.75	3.456	1.312	0.544	0.928	0.224	0	1.024	1.024	1.984	10.496
8	2.944	0.992	1.024	0.512	0.704	0.16	0.288	0.992	2.016	9.632
8.25	3.2	0.288	0.992	0.864	0.416	1.024	1.312	0.992	1.984	11.072
8.5	3.744	0.288	0.992	0.768	0.992	0.992	1.888	0.96	2.016	12.64
8.75	2.368	1.76	0.992	0.064	1.28	0.992	1.984	0.992	1.984	12.416
9	3.616	2.016	0.896	0.224	0.992	0.896	2.016	0.992	2.016	13.664
9.25	2.656	1.088	0.352	0.672	0.736	0.704	1.984	1.024	1.984	11.2
9.5	2.784	1.696	0	0.224	0.992	0.512	2.016	0.064	2.016	10.304
9.75	3.648	1.856	0	0	0.928	0	1.984	0	1.984	10.4
10	3.904	0.992	0	0.64	0.768	0.096	2.016	0.736	2.016	11.168
10.25	3.296	1.408	0.16	1.056	0.512	0	1.984	0	1.984	10.4
10.5	2.208	1.44	0.992	0.96	0.992	0.288	1.728	0	2.016	10.624
10.75	1.632	0.48	0.992	0.96	1.056	1.024	0.032	0	0.8	6.976
11	1.568	0	0.864	0.224	0.864	0.992	0.352	0.288	0.992	6.144
11.25	2.944	0.192	0.992	0.096	0.992	0.128	0.192	0.992	0.992	7.52
11.5	3.744	0.256	0.192	0.448	0.992	0.032	0.896	0.448	0.992	8
11.75	3.136	1.056	0.672	0	0.992	0.928	1.28	0.384	1.792	10.24
12	3.232	0.064	0.512	0	1.024	0.992	1.568	0.64	1.984	10.016
12.25	3.264	0.896	0	0.288	0.992	0.8	1.984	0.672	0.192	9.088
12.5	2.72	0.256	0.128	0.16	0.832	1.024	2.016	0.928	0.896	8.96
12.75	2.784	0.832	0.96	0.736	0.256	0.128	1.984	0.448	1.76	9.888
13	2.56	1.024	0.032	0.672	0.736	0	2.016	0.992	1.728	9.76
13.25	2.368	1.12	0.992	0.992	0.992	0	1.984	0.544	1.856	10.848
13.5	1.28	2.016	0.992	0.992	0	0	2.016	0	1.376	8.672
13.75	3.136	1.888	0.608	0.704	0.32	0	1.952	0	1.184	9.792
14	3.872	1.6	0.992	0.256	0.736	0	1.664	0	1.344	10.464
14.25	3.552	1.344	1.024	0.384	0.608	0	1.984	0	1.984	10.88
14.5	3.232	1.952	0.48	0	1.024	0	2.016	0	0.64	9.344
14.75	2.848	0.032	0	0	0.768	0	0.832	0	0.384	4.864

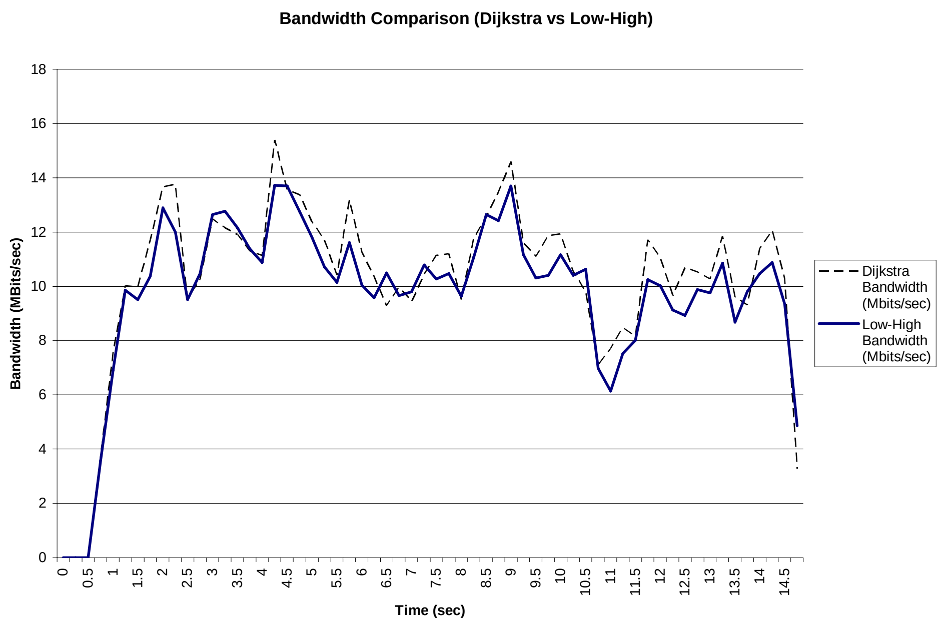

Figure 16. Bandwidth (Dijkstra vs Low-High)

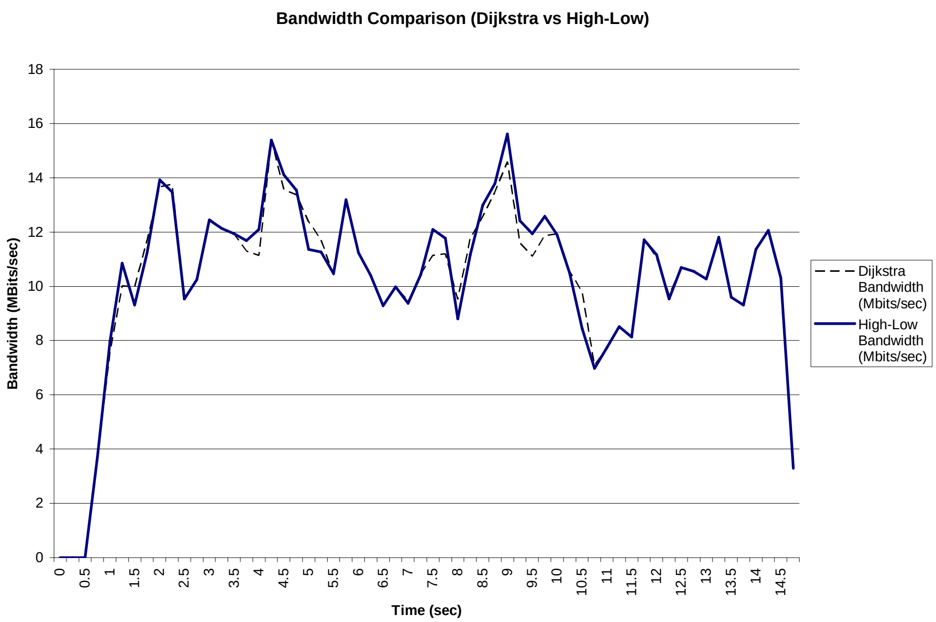

Figure 17. Bandwidth (Dijkstra vs High-Low)

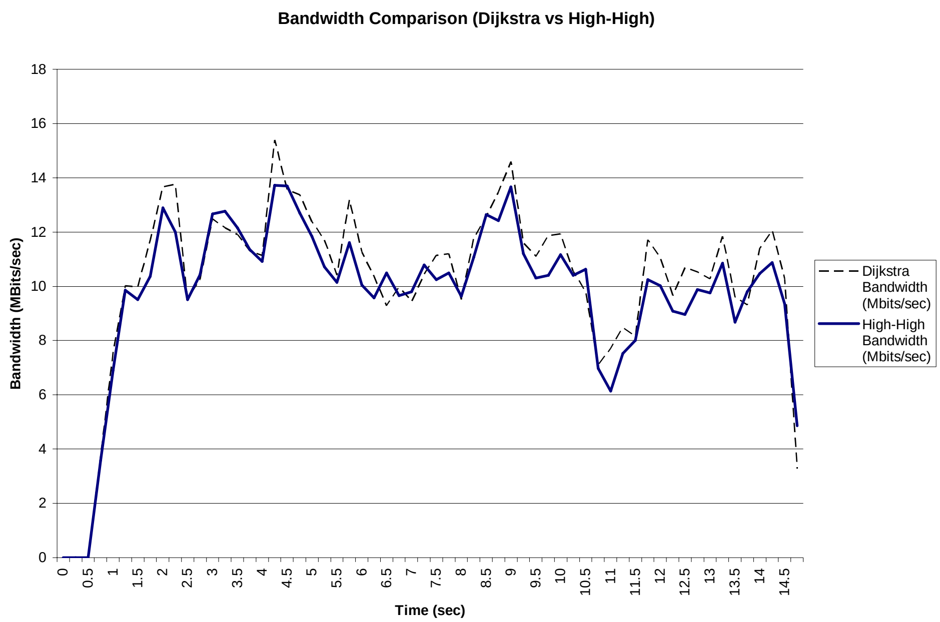

Figure 18. Bandwidth (Dijkstra vs High-High)

Bibliography

Anno, Stephen E. and William E. Einspahr. "Command and Control and Communications Lessons Learned: Iranian Rescue, Falklands Conflict, Grenada Invasion, Libya Raid." Air War College Research Report, No. AU-AWC-88-043, Air University, Maxwell AFB AL, 1988.

Bergzén, Hakan. "Interconnected Communication Networks," *HF Radio systems and Techniques*, Conference Publication 474:29-32 (July 2000).

Cisco Systems Inc., *Internetworking Technology Handbook*, http://www.cisco.com/univercd/cc/td/doc/cisintwk/ito_doc/index.htm, 2005.

Comer, Douglas E. *Internetworking with TCP/IP, Volume I: Principles, Protocols, and Architecture* (4th Edition). Upper Saddle River NJ: Prentice Hall, 2000.

Department of the Air Force. *The U.S. Air Force Transformation Flight Plan 2004.* HQ USAF/XPXC, Washington: 11 CS/SCUS Media Services, 2004.

Durresi, Arjan, Durga Dash, Betty L. Anderson, Rajgopal Kannan, Sastri Kota, and Raj Jain. "Routing of Real-time Traffic in a Transformational Communications Architecture," *Proceedings of 2004 IEEE Aerospace Conference*, Big Sky, MT, March 7-12, 2004, 19 pp.

GlobalSecurity.org. "Transformational Communications Architecture," Draft Factsheet, 15 August 2003. http://www.globalsecurity.org/space/library/report/2003/TCA-Factsheet-DRAFT-15-August-2003.pdf.

Golliday, C. Leslie. "Data Link Communications in Tactical Air Command and Control Systems," *IEEE Journal on Selected Areas in Communication*, SAC-3, 5:779-791 (September 1985).

Gupta, Piyush and P. R. Kumar. "The Capacity of Wireless Networks," *IEEE Transactions on Information Theory*, 46(2):388–404 (March 2000).

Hines, John. "Network Centric Warfare: The Air Network." Briefing to AFIT Research Group, Wright-Patterson AFB OH, 14 January 2005.

Joint Tactical Radio System (JTRS) Joint Program Office (JPO), 2004. http://jtrs.army.mil.

Jumper, John P. Testimony to Congress. Washington DC, 26 September 1999. http://www.house.gov/hasc/testimony/106thcongress/99-10-26jumper.htm.

Meyerriecks, Dawn. "Net-Centric Enterprise Services: What Problems Are We Trying to Solve?" *Military Information Technology, Online Edition*, 7(3) (March 2003). http://www.military-information-technology.com/article.cfm?DocID=23.

Newton, Harry. *Newton's Telecom Dictionary* (17th Edition). New York: CMP Books, 2001.

Perlman, Radia. *Interconnections: Bridges, Routers, Switches and Internetworking* (2nd Edition). Reading MA: Addison-Wesley, 2000.

Peterson, Larry L. and Bruce S. Davie. *Computer Networks: A Systems Approach* (3rd Edition). San Francisco: Morgan Kaufmann, 2003.

Setthawong, Pisai. "Summary of MANET Routing Protocols," The University of Texas at Austin, Austin TX, 2002. http://www.ece.utexas.edu/~pisai/research/.

"Pointers-Communications: Optical Communications," *The Next Wave,* 13(3):34 (2004).

Press, William H., Saul A. Teukolsky, William T. Vetterlink, and Brian P. Flannery. *Numerical Recipes in C: The Art of Scientific Computing* (2nd Edition). Cambridge: Cambridge University Press, 1992.

Teets, Peter B. "Special Briefing On The Opening Of The Transformational Communications Office." Washington DC, 3 September 2002. http://www.defenselink.mil/transcripts/2002/t09042002_t03teets.html.

United States Congress. *The Army's Bandwidth Bottleneck.* Washington:Congressional Budget Office, August 2003.

Winston, Wayne L. *Operations Research: Applications and Algorithms* (3rd Edition). Belmont CA: Duxbury Press, 1994

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 074-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
13 June 2005	Master's Thesis	June 2004 – June 2005

4. TITLE AND SUBTITLE	
A Framework for Routing and Topological Decision-Making Within a Transformational Communications Architecture	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Smith, Alexander I., Major, USAF	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way, Building 641 WPAFB OH 45433-8865	AFIT/GCS/ENG/05-21
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
AFOSR (Dr. Robert Herklotz) 4015 Wilson Blvd Rm 713 Arlington, VA 22203-1954	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A Transformational Communications Architecture (TCA) has been proposed by the US government with the goal of creating "an Internet in the sky." This thesis presents a framework which places user requirements at the heart of routing and topological decision-making within the TCA. It provides new terminology to describe data transmissions and link characteristics and an approach to formulating cost functions to better meet user needs. The framework is intended to stimulate interest and focus efforts on how to meet military specific requirements by taking advantage of the TCA's diverse capabilities and topology. Cost functions using newly-defined parameters are simulated and shown to improve relevant performance over a traditional routing approach.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			SCOTT R. GRAHAM, Maj, USAF
					19b. TELEPHONE NUMBER *(Include area code)*
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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18